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INTELLIGIBILITY PERFORMANCE OF NARROWBAND LINEAR PREDICTIVE VOCODERS IN THE PRESENCE OF BIT ERRORS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Diagnostic speech intelligibility tests were evaluated to assess vulnerability of two different 2400 bit-per-second linear predictive vocoder algorithms to random bit errors imposed on the data stream. Listening tests with crews of eight subjects yielded diagnostic intelligibility scores at zero, 1%, 3%, and 5% bit error rates. These data were analyzed to establish linear regression models relating intelligibility performance and bit error rate. Piecewise-linear prediction coding (PLPC) was confirmed to have a small but significant advantage through being less vulnerable to bit errors than

ABSTRACT (Con't)

conventional linear prediction coding (LPC), an advantage that had been hypothesized from the inherent redundancy that is added by transmitting separate LPC coefficients for low-frequency and high-frequency speech bands. A small but consistent improvement in intelligibility was also found for the error-free case, believed to result from improved spectrum modeling that is a consequence of the piecewise approach. Significant differences in susceptibilities to bit errors were found among individual intelligibility scores for speakers as well as for intelligibility features. Tables for predicting average intelligibility performance, and confidence limits, were constructed from the regression models. The findings provide guidance for further research towards the goal of minimizing susceptibility of narrowband LPC vocoders to jamming and interference. They also highlight a need for further studies to obtain better understanding of causes of the typical large dispersion in intelligibility scores for individual speakers, obtained in these and many other tests. Such knowledge could contribute to improving voice processor designs and to a goal of speech systems that would provide fully adequate intelligibility for 95% or 99% of the population of speakers using these voice communications devices.

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1.0. INTRODUCTION.

The susceptibility to bit errors manifested by different voice digitizer systems represents an important factor for test and evaluation, since it is a performance attribute that provides a measure of the vulnerability of a system to jamming and interference that might be encountered in a military communications environment. Error detection and correction, and other coding schemes imposed on the data stream generated by a voice digitizer can provide valuable means for reducing this susceptibility. This study, however, was concerned with assessing intrinsic vulnerability of two narrowband digital voice communications techniques based on linear predictive coding (LPC), apart from any additional protection that could be added by special coding schemes of bit placement, data smoothing, error detection and correction, etc.

Two LPC-based voice processor algorithms were evaluated. One used a conventional version of LPC-10, a linear predictive coding arrangement in which ten coefficients were calculated from analysis of the speech signal and transmitted together with pitch and energy data in a narrow-band digital representation at 2400 bits per second.

The second version was based on a more recent innovation called "piecewise" linear predictive coding (PLPC), which also utilized analysis and transmission of ten coefficients in a 2400 BPS data stream. However, in this case the LPC coefficients were divided between a low-frequency band of speech (six coefficients) and a high-frequency band (four coefficients). Prior tests and evaluation of the PLPC method have shown that a PLPC(6/4) processor configuration resulted in highly intelligible voice transmission at 2400 BPS. The speech quality was almost indistinguishable from conventional LPC; however, close listening left an impression that the consonant sounds were crisper and clearer than with conventional LPC processing.

The earlier studies led to a conclusion that the PLPC innovation provided advantages both thru a small improvement in speech intelligibility in comparison with conventional LPC, and through relaxing the speed and computational complexity requirements levied on a voice processor terminal. It was hypothesized that the improvement in intelligibility derived from the fact that piecewise modeling of a speech signal contributes to a more accurate representation of a voice than conventional linear predictive coding. The hardware advantages: a lowering of the processor speed requirement, and reduction in the total number of arithmetic operations, offer a potential for designing a voice processor terminal with slower, less costly circuitry, or alternatively, freeing up computational capacity in the processor terminal that could be time-shared to support other functions such as transmitting and receiving modems, signalling and supervision, acoustic noise abatement, etc.

It was further hypothesized that the piecewise-LPC approach would have advantages for reducing vulnerability to bit errors incurred in voice transmission over an imperfect channel. This prediction was based on consideration of the added redundancy provided by the PLPC data format. Since the LPC coefficients for the separate frequency bands are transmitted as independent parameters, when a bit error occurs in one of the coefficient values it can affect only a limited part of the output speech spectrum, rather than affecting the entire voice spectrum as occurs with conventional LPC. With the effect of a bit error segregated to only a portion of the output signal, it was anticipated that the PLPC vocoder design would establish narrowband speech communications providing intelligibility and quality intrinsically less vulnerable to bit errors (and hence to jamming and interference) than a conventional LPC vocoder. An objective of this study was to test this hypothesis.

The comparisons of performance of LPC and PLPC techniques assumed increased importance because of potential advantages foreseen for the PLPC processor in implementation of a multiple-rate processor arrangement capable of supporting wideband as well as narrowband digital speech communications modes. While the piecewise-LPC approach has not yet been investigated in this context, the two prime advantages of PLPC: improved intelligibility, and relaxed hardware requirements, would in principal carry over to a wideband version that provided an additional data component specifying an error signal (residual) for benefits in improved speech quality and naturalness, and tolerance to acoustic noise environments. A voice terminal based on this approach would include an 8 or 9.6 Kbps transmission mode in addition to the 2400 BPS narrowband configuration. By embedding the narrowband voice data in the wideband data stream, special advantages would be obtained for tandem arrangements of wideband and narrowband digital communications channels.

1.1. Susceptibility of Intelligibility Features to Bit Errors.

The Diagnostic Rhyme Test (DRT) used to assess speech intelligibility performance provides assessment of intelligibility scores for the separate components or features that characterize the consonant sounds of speech: voicing, nasality, sustention, sibilation, graveness, and compactness, as well as an overall intelligibility score. An additional objective of this study was to assess the degree to which individual features vary in susceptibility to bit errors. Identification of the features having the greatest vulnerability to bit errors would provide guidance in devising refinements of the speech processing algorithms to minimize bit error effects.

1.2. Susceptibility of individual Speakers to Bit Errors.

Speech intelligibility testing over the past several years has shown consistently that there are large, significant differences in intelligibility scores of different speakers. It was anticipated that different individuals

would vary in regard to the effect of bit errors on their intelligibility scores. This question is important from the point of view of determining confidence limits for predicting the speech intelligibility that might be obtained in various bit error environments. It would be highly desirable to be able to make a reliable forecast of the level of speech intelligibility that could be expected for 95% or 99% of the population of speakers using a digital voice communications channel, both for the condition of an error-free channel and at specified levels of bit error rates due to jamming or interference. These tests with six male speakers and several bit error rates represented a step towards this objective.

1.3. Regression Models relating speech intelligibility scores with bit error rate.

Speech intelligibility data obtained in these tests was used in calculating linear regression models relating the speech intelligibility performance and the bit error rate conditions. Slopes of the regression lines that estimated the intelligibility performance in the presence of bit errors can be interpreted as figures of merit estimating the susceptibility of particular combinations of voice processor, speaker, and intelligibility feature, to the effects of bit errors. The linear regression equations also permitted interpolation and extrapolation to predict the intelligibility that could be expected at additional bit error rates from those actually used in the tests. Confidence limits were also calculated for these estimates.

2.0. TEST AND EVALUATION PROCEDURES.

Intelligibility tests followed general guidelines laid down in previous formal tests for assessing and comparing the intelligibility performance of different voice processor terminals. The salient parameters of the LPC and PLPC voice processing algorithms are summarized in Fig. 1. The voice processor configurations were implemented with software running on the CSP-30 Signal Processor in the Speech Processing Laboratory at Air Force Electronic Systems Division (MCE). Recordings of intelligibility tests were processed with a version of the computer programs that permits random bit errors to be automatically imposed on the data stream at 2400 BPS that connects the voice analyser and synthesizer.

VOICE PROCESSOR CONFIGURATIONS

LPC at 2400 Bits per Second

10th order.
4 Khz bandwidth. 121 usec. sample rate.
172 samples per frame, 20.8 msec frame duration.
Gold-Rabiner pitch extractor.
Interpolation.
(Software documented as Version 4-14-77)

PLPC at 2400 Bits per Second

Two bands; crossover point 20 db down at 2066 Hz.
10 Coefficients total (6, 4)
121 usec. sample rate with downsampling to 88 samples per frame, 21.3 msec frame duration.
Gold-Rabiner pitch extractor.
Interpolation.
(Software documented as Version 3-31-77)

Fig. 1. Salient parameters of the voice processor configurations.

In the real world it is more common for bit errors to occur in bursts or clusters. A random distribution of bit errors was judged to be a more universal case (among the many probability distributions that characterize different combinations of channels, modems, and conditions of the channel) but also a worst case, since the random distribution causes more serious degradation of intelligibility than one in which bit errors occur in clusters. The intelligibility data reported here are conservative, since the intelligibility under typical conditions of wire lines and radio channels in which bit errors are clustered, will probably be higher than the values reported here in which errors were randomly distributed.

2.1. Diagnostic Rhyme Test.

The intelligibility test recordings were based on Form IV of the Diagnostic Rhyme Test (DRT) of Voiers, Mickunas and Cohen, a test that provides both an overall intelligibility score and diagnostic data in the form of separate scores for the various intelligibillty features. The test recordings used as input signals were prepared in an earlier program and were originally recorded in a quiet acoustic chamber using an Altec Model 659A dynamic microphone fixed in a close-talking configuration. (This microphone was chosen on a basis of uniform frequency response and low distortion, as well as minimum tendency for blasting effects in connection with the plosive sounds). Bit error conditions included zero errors, 1%, 3% and 5% bit error rates. Each condition was evaluated by processing DRT recordings from six male speakers (kept constant throughout the battery of tests), each speaker reading 192-word DRT lists in various scramblings.

Recordings of output speech resulting from this processing were subsequently presented diotically over headphones to listener crews of eight naive adults (i.e., unsophisticated with regard to voice processing technology); the listening tests were conducted in the ESD sound room located in the speech lab.

Recordings for evaluation of each bit error rate condition and each processor arrangement (LPC and PLPC) were presented to the listener crew on two different occasions, in a total of sixteen sessions spread over a two month period. (An analysis of variance indicated that the replications did not result in significant variations in test scores). The various findings reported here were derived from analysis of the diagnostic intelligibility data that resulted from analysis of listener responses in those sessions.

2.2. Analysis of variance.

Various subsets of the data were analyzed with three-way analysis of variance (processors, speakers, and bit error rates) to assess qualitatively the significance of differences between intelligibility

scores. For overall intelligibility comparisons, each datum was a total DRT intelligibility score from a single listener; the eight listener scores and two presentations of the recorded test were treated as sixteen replications of the data. Intelligibility scores for the separate features voicing, nasality, sustention, sibilation, graveness, and compactness were each treated as a separate population of scores; in these cases, each datum was an average response of the eight listeners in a given session.

The data groupings were such that the total number of datum points in each of the cells in the analysis of variance was equal. Consequently any lack of homogeneity of variance could be expected to have only small effect on the outcomes of the analysis of variance test results.

Variance ratios were also used in testing for significant differences between slopes of regression lines in making comparisons of the processors, speakers, and intelligibility features in terms of their separate susceptibilities to effects of bit errors.

2.3. Tests of normality, and of equal variance.

The linear regression model is based on assumptions of normality and homogeneity of variance for the distributions of the dependent variable (in this instance, the intelligibility scores). Conformity with these assumptions was tested by means of Lilliefor's test (for conformity with a normal distribution) and Bartlett's test (for Homogeneity of variance) on various data groups consisting of total intelligibility scores, and scores for individual intelligibility features.

2.4. Paired intelligibility scores.

A useful method for assessing the significance of differences in intelligibility scores involves the pairing of scores and an assessment of the distribution of differences between the members of the pairs. In this instance the differences of interest were those between the scores for the LPC voice processor, and the PLPC voice processor, with the pairing representing a common speaker and bit error rate condition. The pairing tended to compensate for average differences between speaker scores, and average differences between scores for different bit error rate conditions, which would tend to conceal small differences in scores for the processor configurations.

The formulations of the various statistical tests are summarized in Appendix I.

3.0. NARROWBAND VOICE PROCESSOR CONFIGURATIONS.

The two versions of linear predictive vocoders that were evaluated were nearly identical in most details, such as the total bandwidth of the voice signal, the sampling rate, the pitch extractor algorithm, and the duration of a data frame. The essential difference was that the conventional LPC algorithm used the linear predictive coding process to model the entire voice spectrum, as opposed to the division of the speech signal into frequency bands and modeling with separate linear predictive coding processes for each band, in the piecewise-LPC configuration. The version of PLPC used in these tests involved a low-frequency band and a high-frequency band, with a crossover point 20 db down at 2066 Hz. The technique involves a low-pass translation of the high band prior to performing the calculations on the data to solve the linear prediction equations. After transmitting LPC coefficients for each of the bands in a combined 2400 BPS data stream, the two bands are separately synthesized at the receiver, followed by a band-pass filtering operation that results in a correctly restored high-frequency band signal. The two bands are then added together to reconstruct the output speech. The method has been described by Roberts and Wiggins (1976).

This sequence of operations in the PLPC processor halves the sample rate involved in the calculations for solving the predictor coefficients (or reflection coefficients) in the speech analyzer, as well as reducing the total number of arithmetic operations in comparison with conventional LPC. In addition to these hardware benefits (for implementing PLPC), the piecewise-LPC method has the advantage of modeling a speech signal with improved accuracy (compared with conventional LPC) as well as providing a new dimension of flexibility for optimizing the assignment and coding of the LPC coefficients in order to derive maximum performance of the processor.

The PLPC configuration used in these tests involved six coefficients assigned to the low frequency band, and four for the high frequency band. There is evidence that the placement of the frequency bands, as well as the assignment and coding of the coefficients, could be refined to obtain further advantages in improving the intelligibility performance in comparison with the scores reported here for the 2400 BPS configuration. In any case, even without this refinement, it will be shown subsequently in this report that the PLPC processor gave higher intelligibility scores than conventional LPC, tending to confirm the hypothesis of improved spectrum modeling. Further refinements of the PLPC algorithm to take advantage of the additional degrees of freedom available for optimizing performance would be expected to further increase this advantage.

4.0. EFFECTS OF BIT ERRORS ON LPC-10 AT 2400 BITS PER SECOND.

Distributions of total DRT intelligibility scores at the four bit error rates are shown in Fig. 2. A detailed listing of total scores is given in Appendix H.

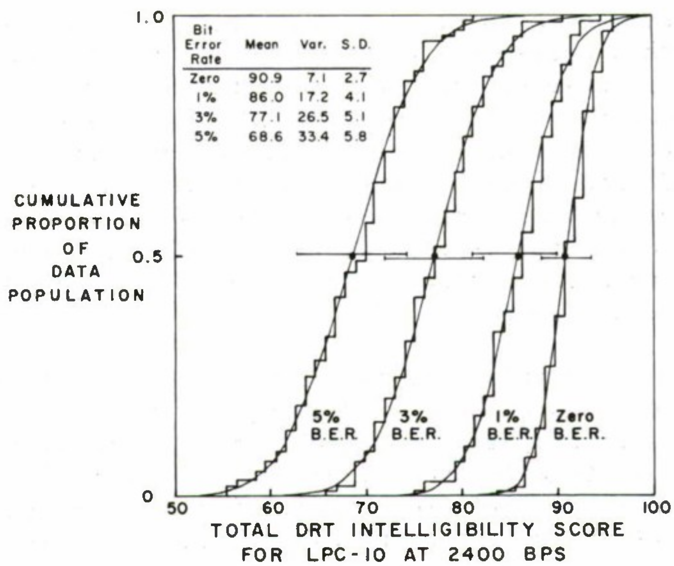


Fig. 2. Distributions of total intelligibility scores for LPC-10.

In these plots the scores have been ranked and plotted as cumulative proportions of the data set, at each of the four bit error rates. Normal ogives based on the calculated mean and standard deviation of each group of data are also shown. As there were six speakers, eight listeners, and two presentations of the test at each bit error rate, there were 96 values for each of the distributions. The Lilliefors test statistic indicated that in three of the four cases the data distributions were reasonable approximations to normal curves. The exception was the distribution for "zero error rate" condition, which indicated significant deviation from the normal ogive. Consequently the hypothesis of a normal distribution for the "zero bit error rate" group of total DRT scores obtained with the LPC-10 processor was rejected (a = .01). The point with excessive deviation occurred in connection with a score of 92.7, which showed a (normalized) deviation of 0.119; the critical value for p = .99 and n = 96 was 0.105.

Bartlett's test for homogeneity of variances indicated that the hypothesis of equal variances for these four distributions should be rejected (a = .001). However, in regard to the interpretation of analysis of variance tests on these data, Scheffe (1959) has pointed out that inequality of variances has much less importance (in biasing the results) when there are equal numbers of datum points in each "cell" of the data, a condition that was satisfied in these analyses.

These data were combined in calculating the linear regression model shown with the scatter plot of scores in Fig. 3. The regression line (the solid line in this figure) presents the expected relationship between total intelligibility scores and bit error rate, for the LPC-10 processor operating at 2400 BPS. The model yielded an estimated score of 90.7 (average score of six male speakers) for the origin of the regression line, corresponding to zero errors, and a negative slope of 4.45, i.e. the intelligibility on the average dropped 4.45 points for each percentage point increase in bit error rate. Standard significance tests (based on assumptions of normality and equal variance, conditions not fulfilled in these distributions) predict that the 95% confidence limits of the slope of the "true" regression line are -4.69 and -4.22. The value of r^2 suggests that .778 of the variation in the total intelligibility scores was related to the variations in bit error rate.

The mean square deviation from the regression line was 20.96 for this data set. Using the standard error, confidence limits were calculated for the expected value estimated by the regression model, and confidence limits for the population of individual datum points. These estimates of predicted performance in the presence of bit errors are summarized in Table 1.

Since the data failed to fulfill the assumptions of normality and homogenous variances required for significance tests of the linear regression model, it was of interest to compare the values predicted by the model with actual values from the data distributions. This result is presented in Table 2. The expected values forecast by the model showed good agreement with average scores at the four bit error rates, estimating slightly lower scores than the actual data at zero bit error rate, and predicting scores slightly higher than those actually obtained at the 5% bit error rate condition. This pattern may be due to the truncation of the range of scores at 100%, or could possibly derive from the fact that the intelligibility drops off at high bit error rates more than a linear model predicts, i.e. that a non-linear model would be more appropriate. The comparison of the values exceeded by 97-1/2% of the datum points may also involve these factors, as well as a tendency for the variance of the intelligibility scores to show a negative correlation with mean scores.

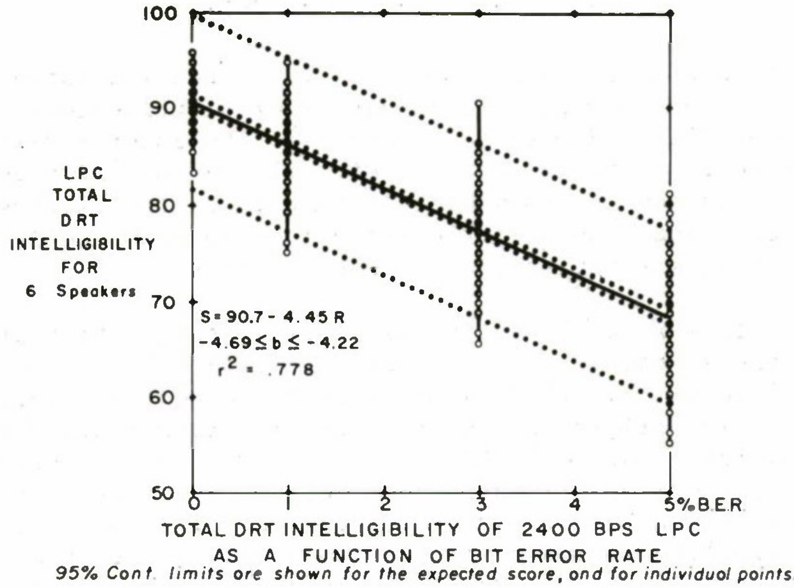


Fig. 3. Scatter plot of scores, and linear regression model for total DRT intelligibility of LPC-10 at 2400 Bits per Second, in the presence of bit errors.

AVERAGE INTELLIGIBILITY vs. Bit Error Rate, for 2400 BPS LPC-10

Model: S(LPC) = 90.66 - 4.454 (BER%) (Based on 384 points)

Bit Error Rate	Total Intelligibility		95% Confidence Limits	
			Expected Avg. Score	Individual Points
0	90.7		89.95 - 91.36	81.63 - 99.69
1	86.2		85.65 - 86.75	77.18 - 95.22
2	81.7		81.28 - 82.21	72.73 - 90.76
3	77.3		76.80 - 77.79	68.28 - 86.31
4	72.8		72.22 - 73.46	63.81 - 81.86
5	68.4		67.58 - 69.19	59.35 - 77.42
6	63.9		62.92 - 64.94	54.87 - 72.99
7	59.5	*Extrapolated*	58.25 - 60.70	50.39 - 68.56
8	55.0	*Values*	53.57 - 56.47	45.90 - 64.14
9	50.6		48.89 - 52.25	41.41 - 59.72
10%	46.1		44.20 - 48.02	36.91 - 55.31

Table I. Predicted Intelligibility performance of LPC-10 at 2400 bits per second in the presence of bit errors (with no provisions for error protection).

COMPARISON OF PREDICTED AND ACTUAL SCORES:

TOTAL INTELLIGIBILITY OF LPC-10 AT 2400 BPS WITH BIT ERRORS

Regression Model: S = 90.7 - 4.45 R

Bit Error Rate	Expected (Avg.) Score		Score Exceeded by 97-1/2% of Speaker/Listener Combinations	
	Regression Model	Actual Data	Regression Model	Actual Data
ZERO	90.7	90.9	81.6	(All: low score 83.3)
1 %	86.2	86.0	77.2	76.0
3 %	77.3	77.1	68.3	68.8
5 %	68.3	66.7	59.4	56.3

Table 2. Comparison of actual intelligibility scores and scores predicted by the linear regression model, for LPC-10 at 2400 bits per second.

4.1. Susceptibility of scores for Intelligibility Features to bit errors: LPC-10 at 2400 bits per second.

Trends in scores of individual intelligibility features derived from the evaluations of LPC-10 processor performance with bit errors are summarized in Table 3. Scores for graveness, summarized in Appendix E, showed the greatest average susceptibility to bit errors, with a slope of -6.39 for overall scores for this feature. The scores for sibilation, presented in Appendix D, were at the other extreme, with an average regression slope of -2.45. Separate linear regression models for each state of these and the other intelligibility features, i.e. with the feature present and absent, voiced and unvoiced, etc. are presented in the Appendices, together with cumulative plots of the distributions of feature scores at the four bit error rates, and tables estimating the predicted intelligibility scores for the features over a range of bit error rates. The regression lines for average scores associated with the six features are compared in Fig. 4.

LINEAR REGRESSION MODELS FOR LPC

Intelligibility Score vs. Bit Error Rate, at 2400BPS
Form: DRT Score = a + b R, where R = B.E.R in percent

Intelligibility Feature	Regression Equation	95% Conf. Limits
VOICING	95.0 - 5.02 R	$-6.37 \le b \le -3.67$
NASALITY	98.6 - 3.73 R	$-4.56 \le b \le -2.91$
SUSTENTION	83.8 - 5.70 R	$-7.16 \le b \le -4.24$
SIBILATION	88.3 - 2.45 R	$-3.56 \le b \le -1.34$
GRAVENESS	83.1 - 6.39 R	$-7.88 \le b \le -4.91$
COMPACTNESS	95.2 - 3.43 R	$-4.38 \le b \le -2.48$
TOTAL Intelligibility	90.7 - 4.45 R	$-4.69 \le b \le -4.22$

Table 3. Summary of linear regression equations describing intelligibility scores for individual features, LPC-10 at 2400 BPS in the presence of bit errors.

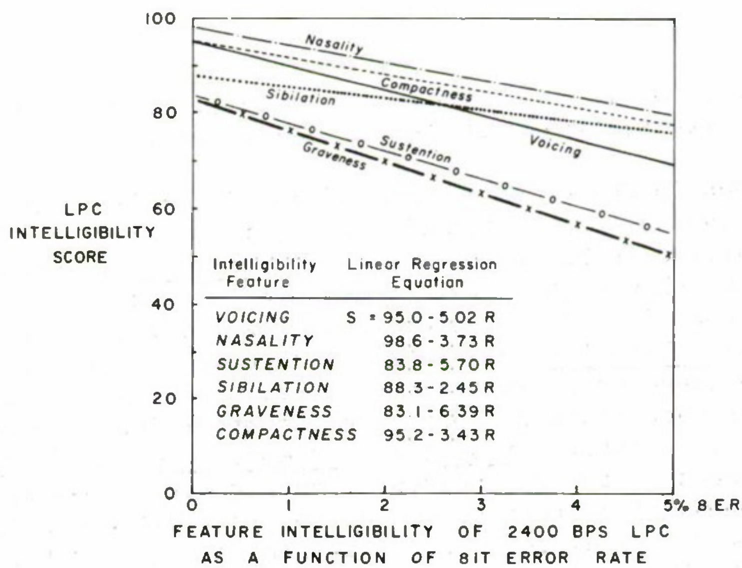


Fig. 4. Linear regression models for individual intelligibility feature scores for LPC-10 at 2400 BPS with bit errors.

ANALYSIS OF VARIANCE: SPEAKER DIFFERENCES

Comparison of Six Speakers' Regression Slopes for

Total DRT Intelligibility Score vs. Bit Error Rate

with 2400 BPS LPC-10

Source of Variation	d.f.	Sum of Squares	Mean Square
Deviations from Regression			
Six Speakers	372	4762.754	12.803
Pooled	372	5189.617	13.950
Diff. in slopes	5	426.863	85.373

Testing H_o: No difference in slopes, $F = \frac{85.373}{12.803} = 6.668^{***}$
Reject H_o

Table 4. Analysis of variance results comparing the regression slopes for total intelligibility scores of individual speakers, LPC-10 at 2400 BPS with bit errors.

4.2. Susceptibility of Intelligibility Scores of individual Speakers to bit error effects: LPC-10 at 2400 BPS.

Linear regression models based on intelligibility scores reflecting the performance obtained with individual speakers were calculated in addition to the regression model for composite performance of all speakers. The regression slopes obtained from these analyses were tested for the hypothesis: no significant difference among slopes for speakers. This result is summarized in Table 4 and Fig. 5. The hypothesis: no difference between the regression slopes estimated for individual speakers, was rejected (a = .001).

Scores for Speaker CH, a speaker who customarily obtains the highest intelligibility scores among this group, resulted in a regression line above the other speakers, and at all points more than 2 points above the next highest, obtained with Speaker BV. Speaker JE, a speaker whose scores are consistently at the bottom of the range, resulted in the lowest regression line and the greatest slope, -5.35.

The Lilliefors test indicated that distributions for total DRT scores of each of the six speakers were reasonable approximations to normal distributions.

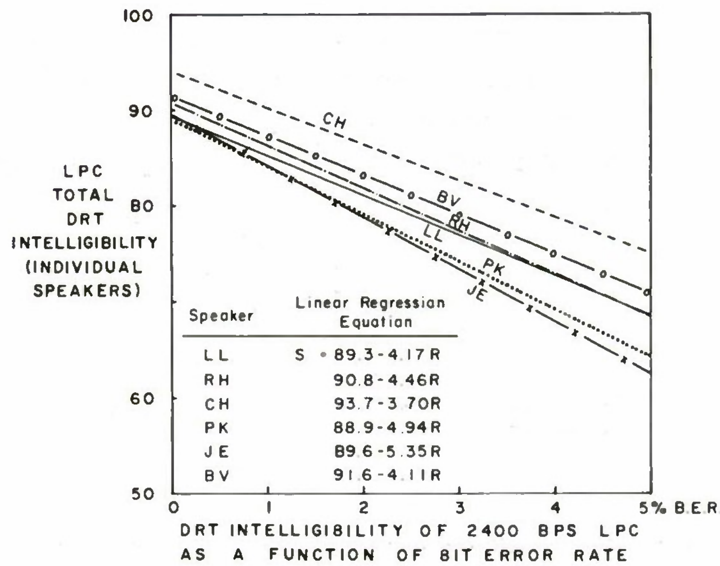


Fig. 5. Linear regression models for individual speaker's total intelligibility scores vs. bit error rate, for LPC-10 at 2400 bits per second.

5.0. EFFECTS OF BIT ERRORS ON PLPC AT 2400 BITS PER SECOND.

Distributions of total DRT intelligibility scores obtained with the PLPC processor operating at 2400 BPS at the four bit error rates are shown in Fig. 6. A detailed listing of total intelligibility scores is presented in Appendix H.

The Lilliefors test statistic indicated that three of the four bit error rate conditions resulted in intelligibility scores that were reasonable approximations to normal distributions. The exception was the distribution for the 1% bit error rate condition; for this case the test indicated significant deviation from a normal curve, and the hypothesis of conformity with a normal curve was rejected (a = .01). The point with excessive deviation corresponded to a total DRT score of 90.62, with a (normalized) deviation of 0.122; the critical value for p = .99 and n = 96 was 0.105. Bartlett's test for homogeneity of variances indicated that the hypothesis of equal variances should be rejected (a = .001). These data followed the usual trend in intelligibility scores, with variance tending to increase with a drop in scores.

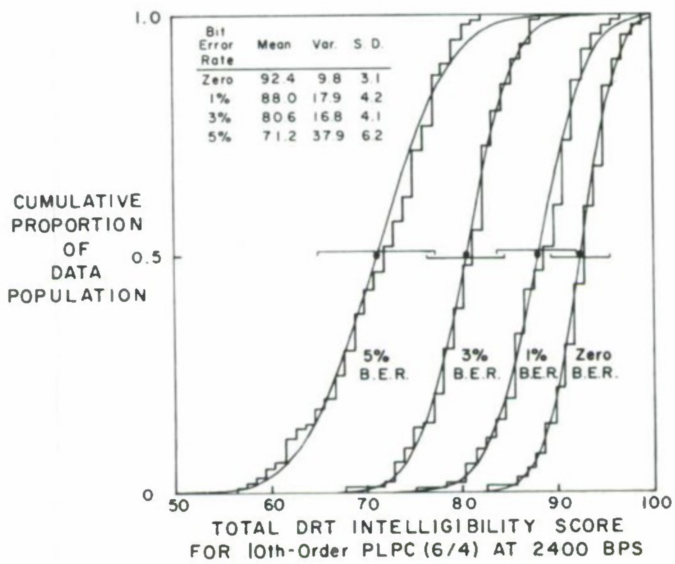
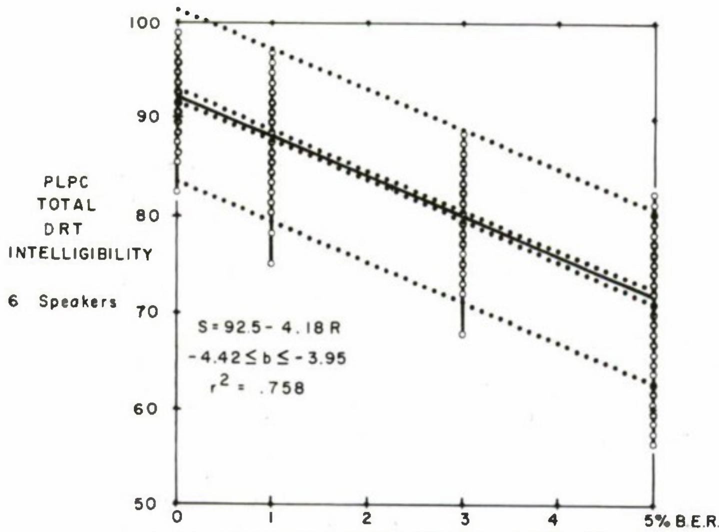


Fig. 6. Distributions of total intelligibility scores for Piecewise Linear Predictive Coding (PLPC).

The linear regression model calculated for total intelligibility scores associated with the PLPC processor is presented in Fig. 7 in relation to the scatter plot of scores. The model estimated a score of 92.5 (six-speaker average score) for the origin of the regression line (zero bit errors) and a slope of -4.18. The standard significance tests estimated that the 95% confidence limits of the "true" regression slope were from -4.42 to -3.95. A comparison of the scores predicted from the regression model and the actual data values is made in Table 6. As with the scores for LPC-10, there was good agreement between the values estimated by the model and the actual data values, even though the data distributions violated some of the underlying assumptions of the model. The comparison exhibits the same trends as the LPC-10 data, in which the predicted values are higher than the actual data, at the 5% bit error rate.



TOTAL DRT INTELLIGIBILITY OF 2400 BPS PLPC
AS A FUNCTION OF BIT ERROR RATE
95% Conf. limits are shown for the expected score, and for individual points.

Fig. 7. Scatter plot of scores, and linear regression model for total DRT intelligibility of PLPC at 2400 bits per second, in the presence of bit errors.

AVERAGE INTELLIGIBILITY vs. Bit Error Rate for 2400 BPS PLPC

Model: S(PLPC) = 92.46 − 4.184(BER%) (Based on 384 points)

Bit Error Rate	Total Intelligibility		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Points
0	92.5		91.75 - 93.16	83.49 - 101.42
1	88.3		87.73 - 88.81	79.31 - 97.23
2	84.1		83.63 - 84.55	75.13 - 93.04
3	79.9		79.41 - 80.39	70.95 - 88.85
4	75.7		75.10 - 76.33	66.76 - 84.68
5	71.5		70.74 - 72.33	62.56 - 80.51
6	67.3	↓	66.35 - 68.35	58.35 - 76.34
7	63.2	*Extrapolated*	61.95 - 64.38	54.14 - 72.19
8	59.0	*Values*	57.54 - 60.42	49.93 - 68.03
9	54.8		53.13 - 56.46	45.70 - 63.89
10%	50.6		48.71 - 52.51	41.47 - 59.75

Table 5. Predicted intelligibility performance of PLPC at 2400 bits per second in the presence of bit errors (with no provisions for error protection).

COMPARISON OF PREDICTED AND ACTUAL SCORES:
TOTAL INTELLIGIBILITY OF PLPC AT 2400 BPS WITH BIT ERRORS
Regression Model: $S = 92.5 - 4.18 R$

Bit Error Rate	Expected (Avg.) Score		Score Exceeded by 97-1/2% of Speaker/Listener Combinations	
	Regression Model	Actual Data	Regression Model	Actual Data
ZERO	92.5	92.4	83.5	85.4
1 %	88.3	88.0	79.3	80.2
3 %	79.9	80.6	71.0	72.9
5 %	71.5	71.2	62.6	58.3

Table 6. Comparison of actual intelligibility scores and scores predicted by the linear regression model, for PLPC at 2400 bits per second.

5.1. Susceptibility of scores for Intelligibility Features to bit errors: PLPC at 2400 bits per second.

Linear regression equations representing the average trends in scores for the individual intelligibility features are summarized in Table 7. The analysis indicated a pattern of susceptibility to bit errors similar to that obtained with LPC-10, in which the scores for the feature graveness with an average slope of -5.75 indicated the greatest susceptibility, scores for sibilation with an average slope of -3.35 evidencing the least susceptibility. Regression lines for average scores for the six principal features are compared in Fig. 8. Detailed listings of scores for the separate features and cumulative distributions are presented in the Appendices, as well as tables predicting feature scores over a range of bit error rates.

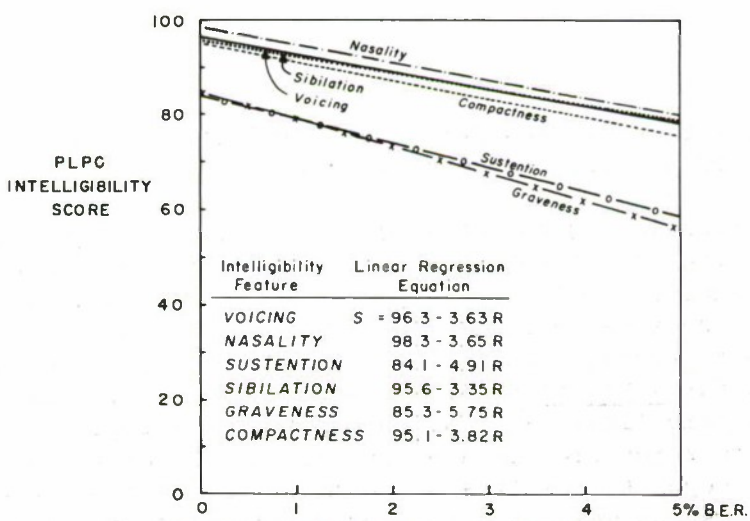
LINEAR REGRESSION MODELS FOR PLPC

Intelligibility Score vs. Bit Error Rate, at 2400 BPS

Form: DRT Score = a + b R, where R = B.E.R. in percent

Intelligibility Feature	Regression Equation	95% Conf. Limits
VOICING	96.3 - 3.63 R	$-4.66 \le b \le -2.59$
NASALITY	98.3 - 3.65 R	$-4.48 \le b \le -2.83$
SUSTENTION	84.1 - 4.91 R	$-6.33 \le b \le -3.50$
SIBILATION	95.6 - 3.35 R	$-4.10 \le b \le -2.60$
GRAVENESS	85.3 - 5.75 R	$-7.34 \le b \le -4.15$
COMPACTNESS	95.1 - 3.82 R	$-4.87 \le b \le -2.77$
TOTAL Intelligibility	92.5 - 4.18 R	$-4.42 \le b \le -3.95$

Table 7. Summary of linear regression equations describing intelligibility scores for individual features, PLPC at 2400 BPS in the presence of bit errors.



FEATURE INTELLIGIBILITY OF 2400 BPS PLPC AS A FUNCTION OF BIT ERROR RATE

Fig. 8. Linear regression models for individual intelligibility feature scores for PLPC at 2400 BPS with bit errors.

5.2. Susceptibility of intelligibility scores of individual Speakers to bit error effects: PLPC at 2400 bits per second.

Total DRT intelligibility scores obtained with each of the six speakers tested in combination with the PLPC processor were utilized in separate calculations of linear regression models, tests for normality of the distributions of scores, and for equal variances. An analysis of variance testing the hypothesis of no difference in slopes of the regression lines of the six speakers indicated that the hypothesis of equal regression slopes should be rejected (a = .001). This finding is summarized in Table 8.

Linear regression models based on total scores for each of the six speakers in tests of PLPC are presented in Fig. 9.

ANALYSIS OF VARIANCE: SPEAKER DIFFERENCES

Comparison of Six Speakers: Regression Slopes for

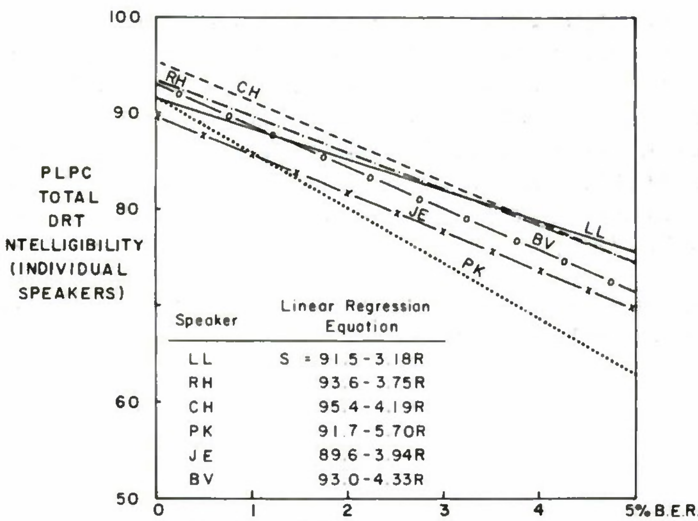
Total DRT Intelligibility Score vs. Bit Error Rate

with 2400 BPS Piecewise - LPC

Source of Variation	d.f.	Sum of Squares	Mean Square
Deviations from Regression			
Six Speakers	372	4642.071	12.479
Pooled	372	5487.151	14.750
Diff. in slopes	5	845.081	169.016

Testing H_o: No difference in slopes, $F = \frac{169.016}{12.479} = 13.544^{***}$
Reject H_o

Table 8. Analysis of variance results comparing the regression slopes for total intelligibility scores of individual speakers, PLPC at 2400 BPS with bit errors.



DRT INTELLIGIBILITY OF 2400 BPS PLPC
AS A FUNCTION OF BIT ERROR RATE

Fig. 9. Linear regression models for individual speaker's total intelligibility scores vs. bit error rate, for PLPC at 2400 BPS.

6.0. COMPARISONS OF PERFORMANCE OF LPC AND PLPC OPERATING AT 2400 BITS PER SECOND IN THE PRESENCE OF BIT ERRORS.

A variety of statistical tests were performed on the speech intelligibility scores to test the hypothesis that the LPC and PLPC processor configurations differed significantly in terms of speech intelligibility performance.

6.1. Analysis of variance findings.

Results of a battery of three-way analysis of variance tests are summarized in Tables 9.1 and 9.2; the three-way classification was by processors, speakers and bit error rates. Detailed summaries with sums of squares, mean squares, and variance ratios are given in the Appendices, together with the data tables that were the basis for these results.

THREE-WAY ANALYSIS OF VARIANCE: SUMMARY OF RESULTS OF COMPARING 2400 BPS LPC AND PLPC INTELLIGIBILITY SCORES

INTELLIGIBILITY FEATURE	SIGNIFICANT DIFFERENCES PROCESSORS (LPC & PLPC)	SPEAKERS (6 Males)	Bit Error Rates (Four BER's)
VOICING	** (p=.997)	*** (p=.999)	*** (p=.999)
Present	*** (p=.999)	*** (p=.999)	*** (p=.999)
Absent	———	*** (p=.999)	*** (p=.999)
NASALITY	———	———	*** (p=.999)
Present	* (p=.954)	*** (p=.999)	*** (p=.999)
Absent	———	*** (p=.999)	*** (p=.999)
SUSTENTION	———	*** (p=.999)	*** (p=.999)
Voiced	* (p=.988)	*** (p=.999)	*** (p=.999)
Unvoiced	———	*** (p=.999)	*** (p=.999)
SIBILATION	*** (p=.999)	*** (p=.999)	*** (p=.999)
Voiced	** (p=.998)	** (p=.997)	*** (p=.999)
Unvoiced	*** (p=.999)	*** (p=.999)	*** (p=.999)
GRAVENESS	* (p=.985)	* (p=.988)	*** (p=.999)
Voiced	* (p=.961)	———	*** (p=.999)
Unvoiced	———	** (p=.998)	*** (p=.999)
COMPACTNESS	———	*** (p=.999)	*** (p=.999)
Voiced	———	*** (p=.999)	*** (p=.999)
Unvoiced	———	*** (p=.999)	*** (p=.999)
TOTAL INTELLIGIBILITY	*** (p=.999)	*** (p=.999)	*** (p=.999)

Table 9.1. Three-way analysis of variance results comparing intelligibility scores for LPC-10 and PLPC at 2400 BPS in the presence of bit errors.

The analysis of variance was predicated on a fixed-effects model, from a rationale that the six speakers were common to the entire battery of tests, as were the majority of the listener crew. A case can also be made for a mixed-effects model, from the reasoning that the random bit error effects involved successive samplings of a randomly distributed variable. The tables of mean squares listed in the Appendices are provided in order to permit the option of calculating significance tests from this alternative point of view.

The analysis of variance indicated that about half of the intelligibility scores for individual features, as well as the total scores, evidenced significant differences between the LPC and PLPC processor configurations. All of the feature scores showed significant differences due to bit error rate conditions, and nearly all were characterized by significant differences between the six speakers.

The analysis of variance also revealed that significant interactions between processors and speakers were present for the majority of the intelligibility features, as well as total intelligibility scores. The total scores, and a few feature scores, showed significant interactions between speakers and bit error rates, and between processors and bit error rates. These results are summarized in Table 9.2.

A further group of tests were conducted on total intelligibility scores at each of the four bit error rates, testing the significance of the difference in mean scores for the LPC and PLPC processors. These results are summarized in Table 10.

THREE-WAY ANALYSIS OF VARIANCE: SUMMARY OF RESULTS OF COMPARING 2400 BPS LPC AND PLPC INTELLIGIBILITY SCORES

INTELLIGIBILITY FEATURE	SIGNIFICANT INTERACTIONS: Processors and Speakers	Processors and Bit Error Rates	Speakers and Bit Error Rates
VOICING	* (p = .956)	———	———
Present	*** (p = .999)	*** (p = .999)	*** (p = .999)
Absent	———	———	———
NASALITY	*** (p = .999)	———	———
Present	*** (p = .999)	———	*** (p = .999)
Absent	** (p = .990)	———	*** (p = .999)
SUSTENTION	** (p = .993)	———	———
Voiced	* (p = .977)	* (p = .979)	** (p = .995)
Unvoiced	** (p = .998)	———	* (p = .965)
SIBILATION	** (p = .996)	———	———
Voiced	** (p = .996)	———	———
Unvoiced	*** (p = .999)	———	———
GRAVENESS	———	———	———
Voiced	———	———	———
Unvoiced	———	———	———
COMPACTNESS	———	———	———
Voiced	** (p = .995)	———	———
Unvoiced	*** (p = .999)	** (p = .994)	———
TOTAL INTELLIGIBILITY	*** (p = .999)	* (p = .974)	*** (p = .999)

Table 9.2. Significant interactions revealed in the three-way analysis of variance summarized in Table 9.1.

COMPARISON OF MEAN INTELLIGIBILITY SCORES

Six Speakers, Two Replications, per Condition

	LPC	PLPC	Diff.(1)	F (with 1 & 165 d.f.)
Zero Bit Errors	90.92	92.39	1.48	21.638*** (p>.999)
1%	85.98	88.01	2.03	20.822*** (p>.999)
3%	77.08	80.58	3.49	44.360*** (p>.999)
5%	68.55	71.18	2.63	18.443*** (p>.999)

(1) Differences in avg. scores were significant at the .001 level.

Table 10. Comparison of total DRT intelligibility scores obtained with LPC-10 and with PLPC at each bit error rate condition.

Differences between mean intelligibility scores (six speakers) for the LPC and PLPC processors, although small, were highly significant at each bit error rate condition. Distributions of the total scores at each bit error rate condition are compared in Figs. 10 through 13, with the normal ogive based on the mean score and standard deviation of the data in each distribution shown for comparison. In every case, the piecewise-LPC processor obtained a higher intelligibility score than the conventional LPC processor configuration.

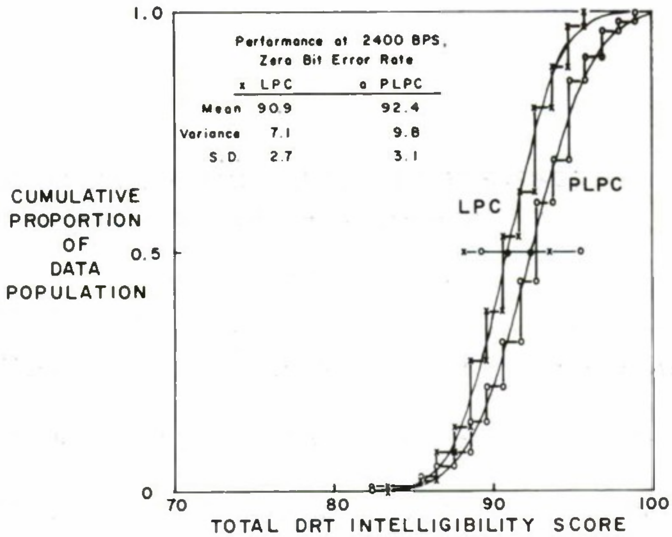


Fig. 10. Comparison of distributions of total DRT intelligibility scores for LPC and PLPC at 2400 BPS with zero bit error rate.

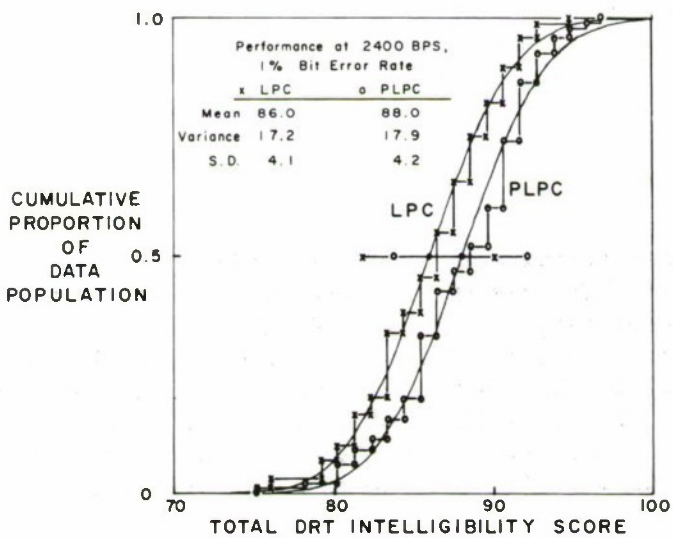


Fig. 11. Comparison of distributions of total DRT intelligibility scores for LPC and PLPC at 2400 BPS with 1% bit error rate.

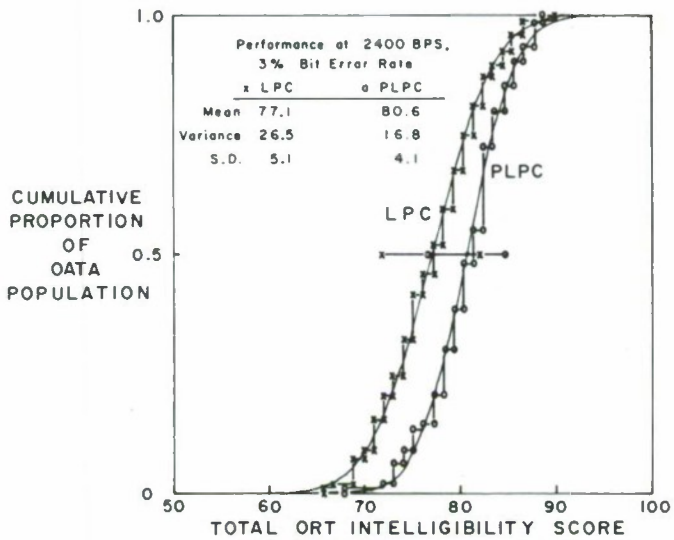


Fig. 12. Comparison of distributions of total DRT intelligibility scores for LPC and PLPC at 2400 BPS with 3% bit error rate.

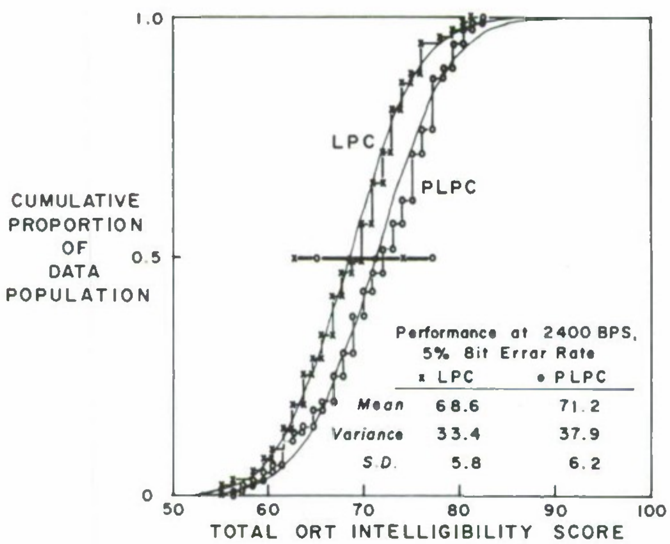


Fig. 13. Comparison of distributions of total DRT intelligibility scores for LPC and PLPC at 2400 BPS with 5% bit error rate.

6.2. Pairwise comparison of intelligibility scores.

The intelligibility scores for LPC and PLPC processor configurations were further compared through a pairwise comparison of scores. The pairing involved an LPC intelligibility score, and a PLPC score, for a common speaker and bit error rate condition. The distribution of differences in scores, between the members of the pairs, was utilized in testing for the significance of the average difference between the performance of the LPC and the PLPC processors, over all bit error rate conditions and speakers. The pairing had the effect of normalizing against variance due to speaker effects and bit error effects that would otherwise tend to mask out the significance of small differences between the performance of the processors. Cases in which the score for the LPC processor was significantly better than the PLPC processor are shown in Table 11.1; cases showing a significant advantage for PLPC in Table 11.2.

COMPARISONS OF LPC AND PIECEWISE-LPC AVERAGE INTELLIGIBILITY SCORES

Zero, 1%, 3% and 5% Bit Error Rates at 2400 BPS

PART I. SIGNIFICANT DIFFERENCES FAVORING LPC

INTELLIGIBILITY FEATURE	FEATURE PRESENT	FEATURE ABSENT	FEATURE AVERAGE
VOICING (Avg.)	–	–	–
Frictional	–	–	–
Non-Frictional	–	5.08*	–
NASALITY (Avg.)	–	–	–
Grave	–	–	–
Acute	–	–	–
SUSTENTION (Avg.)	–	–	–
Voiced	–	–	–
Unvoiced	–	–	–
SIBILATION (Avg.)	–	–	–
Voiced	–	–	–
Unvoiced	–	–	–
GRAVENESS (Avg.)	–	–	–
Voiced	–	–	–
Unvoiced	–	–	–
COMPACTNESS (Avg.)	3.22*	–	–
Voiced	4.43*	–	–
Unvoiced	–	–	–
TOTAL DRT INTELLIGIBILITY SCORE:	–		

Table 11.1. Results of pairwise-comparison of LPC and PLPC intelligibility scores: Differences favoring LPC-10.

COMPARISONS OF LPC AND PIECEWISE-LPC AVERAGE INTELLIGIBILITY SCORES

Zero, 1%, 3% and 5% Bit Error Rates at 2400 BPS

PART 2. SIGNIFICANT DIFFERENCES FAVORING PIECEWISE-LPC

INTELLIGIBILITY FEATURE	FEATURE PRESENT	FEATURE ABSENT	FEATURE AVERAGE
VOICING (Avg.)	10.91***	–	4.49**
Frictional	8.79***	–	5.01**
Non-Frictional	13.02**	–	–
NASALITY (Avg)	–	–	–
Grave	5.14**	–	–
Acute	–	–	–
SUSTENTION (Avg.)	–	–	–
Voiced	–	6.19*	5.11*
Unvoiced	–	–	–
SIBILATION (Avg.)	9.99***	–	5.21***
Voiced	12.57***	–	5.18**
Unvoiced	7.42**	3.06*	5.24***
GRAVENESS (Avg.)	–	7.00***	3.66**
Voiced	–	–	3.06*
Unvoiced	–	11.85***	4.26*
COMPACTNESS (Avg.)	–	–	–
Voiced	–	–	–
Unvoiced	–	–	–
TOTAL ORT INTELLIGIBILITY SCORE:		2.41***	

Table II.2. Results of pairwise-comparison of LPC and PLPC intelligibility scores: Differences favoring PLPC.

As there are nine cases associated with each of the intelligibility features, i.e. three scores when the feature was present (for example, voiced, unvoiced, and total of voiced and unvoiced cases), three for the feature absent, and three for the total cases for present and absent, a total of 54 diagnostic intelligibility scores are involved in the total summary, plus a total score for overall intelligibility. Thus the results of the pairwise tests represented 55 separate assessments resulting in a detailed listing of salient differences of intelligibility performance for the two processors. In approx. two-thirds of these cases, the difference was not statistically significant. The significant differences, shown in these tables, included three cases favoring LPC, and twenty

cases, as well as the overall intelligibility scores, showing a significant bias favoring the PLPC processor.

6.3. Comparison of regression slopes: LPC and PLPC total DRT intelligibility scores vs. bit error rate.

Further comparisons of the LPC and PLPC total intelligibility scores were made in comparing their susceptibilities to bit errors as estimated by the slopes of the regression lines relating intelligibility and bit error rate. An analysis of variance was made to test the hypothesis: no difference in regression slopes. The test was performed with the composite data for all six speakers; separate tests were also made comparing the regression slopes calculated for LPC and PLPC on a speaker-by-speaker basis.

The results of testing the composite data are shown in Table 12.1. (The basis of the test is summarized in Appendix I.) The difference between the regression slope calculated for the LPC processor scores (-4.45) and the slope calculated for the PLPC scores (-4.18) was not significant, either in the original data or after an adjustment for differences in speaker means. However, comparing the LPC and PLPC regression lines, speaker by speaker, it was revealed that the scores for four of the six speakers showed a significant advantage for the PLPC processor. The difference in slopes for the remaining two speakers was not significant. This result is summarized in Table 12.2.

ANALYSIS OF VARIANCE: PROCESSOR DIFFERENCES

Comparing 2400 BPS LPC and Piecewise-LPC Regression Slopes

for Total DRT Intelligibility Score vs. Bit Error Rate

Source of Variance	d.f.	Sum of Squares	Mean Square
Deviations from Regression			
Processors (LPC & PLPC)	764	15902.556	20.815
Pooled	764	15953.429	20.882
Diff. in slopes	1	50.873	50.873

Testing H_0: No difference in slopes, $F = \frac{50.873}{20.815} = 2.444$ ($p = .882$)

Adjusted for Speaker differences:

Source of Variance	d.f.	Sum of Squares	Mean Square
Deviations from Regression			
Processors (LPC & PLPC)	764	11201.151	14.661
Pooled	764	11252.801	14.729
Diff. in slopes	1	51.650	

Testing H_0: No difference in slopes, $F = \frac{51.650}{14.661} = 3.523$ ($p = .939$)

Table 12.1. Analysis of variance summary comparing linear regression slopes: total DRT intelligibility scores for LPC-10 and PLPC. (All speakers).

ANALYSIS OF VARIANCE: PROCESSOR DIFFERENCES

Comparing 2400 BPS LPC and Piecewise - LPC Regression Slopes

by Individual Speakers' Total Intelligibility Score vs. Bit Error Rate

Testing H_0: No difference in slopes

SPEAKER	b = slope LPC	b = slope PLPC	F = Variance ratio (with 1 and 124 d.f.)		
LL	-4.17	-3.18	9.117**	(p = .997)	REJECT H_0
RH	-4.46	-3.75	4.552*	(p = .965)	REJECT H_0
CH	-3.70	-4.19	3.756	(p = .945)	
PK	-4.94	-5.70	4.355*	(p = .961)	REJECT H_0
JE	-5.35	-3.94	16.818***	(p = .999)	REJECT H_0
BV	-4.11	-4.33	0.459		

Table 12.2. Analysis of variance results comparing linear regression slopes, total intelligiblity scores for LPC-10 and PLPC, by individual speakers.

6.5. Comparisons of regression slopes: intelligibility feature scores for LPC and PLPC processors, vs. bit error rate.

Tests of the scores for individual intelligibility features revealed that the majority of the distributions of feature scores at the various bit error rates failed to meet the requirements of being normally distributed, and of equal variances at the various bit error rates. Significance tests of the regression data are therefore in question; however, the results of these tests may have value in contributing to understanding of the nature and degree of difference in intelligibility performance of the LPC and PLPC processors in the presence of bit errors.

Detailed tables of regression equations and estimates of the 95% confidence limits for the slopes for the various feature scores are contained in Appendix G; tables comparing the feature scores predicted by the regression models, and the actual data, are also presented. A portion of this data was examined in analysis of variance tests of the difference in regression slopes for the LPC and PLPC processor scores. The results are presented in Table 13. Of the eighteen cases that were tested, eleven showed a smaller slope for the PLPC scores, i.e. estimated

smaller susceptibility to bit errors. Seven of the comparisons showed the opposite bias, favoring LPC. However, the variance ratios did not exceed the critical value in any of these tests; as a result, the hypothesis of no difference in regression slopes was not rejected. Speaker variability, and the smaller number of datum points involved in these comparisons, were factors that influenced this outcome.

Intelligibility Feature Scores vs. Bit Error Rate

Testing H_o: No difference in slopes

INTELLIGIBILITY FEATURE	b = SLOPE LPC	PLPC	F	(d.f.)	p
VOICING (Avg.)	-5.02	-3.63	2.611	(1,380)	0.893
Frictional	-4.41	-3.58	0.549	(1,188)	
Non-Frictional	-5.63	-3.67	2.306	(1,188)	0.869
NASALITY (Avg.)	-3.73	-3.65	0.019	(1,380)	
Grave	-4.01	-3.57	0.252	(1,188)	
Acute	-3.46	-3.74	0.126	(1,188)	
SUSTENTION (Avg.)	-5.70	-4.91	0.585	(1,380)	
Voiced	-7.19	-4.45	3.206	(1,188)	0.925
Unvoiced	-4.21	-5.37	0.894	(1,188)	
SIBILATION (Avg.)	-2.45	-3.35	1.772	(1,380)	0.816
Voiced	-2.30	-2.61	0.119	(1,188)	
Unvoiced	-2.60	-4.09	2.195	(1,188)	0.860
GRAVENESS (Avg.)	-6.39	-5.75	0.346	(1,380)	
Voiced	-5.26	-4.91	0.151	(1,188)	
Unvoiced	-7.53	-6.58	0.501	(1,188)	
COMPACTNESS (Avg.)	-3.43	-3.82	0.291	(1,380)	
Voiced	-2.48	-1.98	0.583	(1,188)	
Unvoiced	-4.38	-5.66	1.529	(1,188)	0.782

Accept H_o: No difference in regression slopes

Table 13. Comparison of linear regression slopes derived from individual intelligibility feature scores, for LPC-10 and PLPC.

7.0. DISCUSSION OF FINDINGS.

Tables of intelligibility scores for the various features, cumulative plots of the distributions of scores, and scatter diagrams shown in relation to linear regression lines are presented in the Appendices. Some of the salient findings from analysis of this data are presented in the following paragraphs.

The Lilliefors test, described in Appendix I.2., indicated that the hypothesis of a normal distribution of scores should be rejected for a majority of the data groupings of intelligibility scores for individual intelligibility features. Deviation from a normal distribution appeared to derive from three primary causes, singly or in combination: (1) truncation of the range of scores at 100%; (2) significant differences among mean scores for individual speakers; and (3) significant differences among mean scores for the feature states, e.g. the Voicing scores included Voicing Present (frictional and non-frictional) and Voicing Absent (frictional and non-frictional), etc. Total intelligibility scores, representing the summation of these effects, were better approximations to normal curves, as reported in earlier sections of this report.

Even with these departures from the assumptions underlying the linear regression model, the expected feature scores predicted by the regression models for the features on the whole agreed well with the actual data; these comparisons are presented in Appendix G.5.

The distributions of intelligibility scores were also characterized by a tendency to show a significant negative correlation between mean scores and variance associated with the distributions (as has been found generally in intelligibility testing). In many cases, the assumption of homogeneity of variance required for the linear regression model tests of significance was not fulfilled in the data. A result of these distortions (relative to the model) was a tendency for the confidence limits predicted by the model to be conservative at zero bit error rate: most or all of the data values were above the lower 95% confidence limit for individual scores. However, at the upper end of the range (5% bit error rate) the model was overly optimistic: a larger percentage of datum points were below the confidence limit than predicted by the model. The overall scores for LPC-10 illustrate this trend: at zero bit error rate, all of the scores were above the lower 95% limit estimated by the model. At the 5% bit error rate, almost 10% of the datum points were outside the 95% limits estimated for individual points, an equal number of points occurring above and below the limits. Total intelligibility scores including all bit error rates showed a remarkable "global" agreement with the model, however, in that 19 out of 384 points (4.9%) were distributed outside the 95% limits for individual datum points

estimated by the regression models, with each processor's scores (LPC and PLPC).

These departures from the assumptions that underly the linear regression model must be kept in mind in interpreting the various results of significance tests on the linear regression data, in particular the estimates for 95% confidence limits for slopes of the regression lines, and 95% confidence limits that have been estimated for predicting distributions of individual scores at different bit error rates. Lacking for the present any data base or alternative method for estimating these limits with greater reliability, these data are presented in order to provide estimates for the values.

7.1. Comparison of LPC and PLPC processor algorithms.

There were no special provisions in the LPC and PLPC processor algorithms involved in these tests that were specifically designed to alleviate the effects of bit errors: provisions such as optimum placement of bits in the data frame, smoothing of the parameters prior to speech synthesis, error detection and correction, etc, techniques known to be of value in minimizing effects of bit errors on speech intelligibility and quality. The purpose here was to assess and compare the intrinsic vulnerability of the LPC and PLPC speech processing algorithms to bit errors, and to perform a definitive test of the hypothesis that the inherent redundancy and improved spectral modeling provided by the PLPC approach improve the intelligibility of the speech signals from a PLPC-based processor design, in comparison with a conventional LPC design, with and without bit error effects.

The test results provided clear confirmation of this hypothesis. Although the numerical value of the difference in performance was in most cases small, its statistical significance was confirmed in numerous tests.

Error detection and correction, and other special coding schemes to reduce effects of bit errors can of course improve the performance of a conventional LPC processor terminal in comparison with these results for which no such provisions were present. However, these test results suggest that the application of these schemes to the PLPC algorithm should in every case provide more beneficial results in improving speech intelligibility and quality than when applied to the LPC algorithm, other things being equal. This conclusion stems from the basic advantages of the piecewise linear predictive coding method that have been previously cited: better spectral modeling

derived from the piecewise approach, and segregation of bit error effects involving LPC coefficients to only a portion of the output speech spectrum, rather than the entire spectrum as happens with conventional LPC.

As a further consideration, the PLPC algorithm used in these tests was not an optimum design. There is considerable evidence that changes in the combination of frequency bands and the coding of the coefficients could lead to a further increment of improvement in the performance attained in connection with the PLPC algorithm: refinements that are possible with the PLPC configuration because of the additional degree of freedom provided with the use of multiple frequency bands. These changes would be minor in terms of hardware and software, but have a high probability of leading to significant results in improving the performance in both the error-free condition and in the presence of bit errors. Similar considerations are involved in connection with the acoustic noise problem: the separation of the speech signal into frequency bands affords an additional degree of flexibility in refinement of the algorithm to combat effects of acoustic noise.

Some details of the contrasts in intelligibility scores for the various intelligibility features are described in the following paragraphs.

A comparison of the data distributions of intelligibility scores for Voicing Present in comparison with Voicing Absent obtained with the LPC processor revealed that the difference in susceptibility to bit errors (as estimated by the regression slopes) was significant only for the non-frictional sounds, involving voiced and unvoiced initial stop consonants. Here the regression slope was -8.12 for Voicing Present, and -3.14 for Voicing Absent. Although in this case the unvoiced sounds were not as susceptible to bit errors as the voiced sounds, the reverse was true in the case of the voiced and unvoiced states associated with the features Graveness and Compactness, as will be described in the discussion of those features. The test words and intelligibility data for the Voicing feature are presented in Appendix A; a complete table of regression equations relating intelligibility scores with bit error rate for the various intelligibility feature states is presented in Appendix G.

In the case of intelligibility scores for the PLPC processor, the difference in regression slopes for Voicing Present vs. Voicing Absent was significant for both the frictional case (a = .05) and the non-frictional case (a = .001).

Intelligibility scores for the Nasality feature, listed in Appendix B, indicated that neither the contrast between Nasality Present and Nasality Absent, or the contrast between Nasality(Grave) and Nasality(Acute) evidenced significant differences in values of the regression slope in the case of performance data for the LPC processor. However, the distributions of scores for the PLPC processor showed a significant difference between the regression slopes for Nasality Present (b = -2.58) and Nasality Absent (b = -4.73) at the level a = .01.

The test words and intelligibility scores for the Sustention feature are listed in Appendix C. Scores obtained with the LPC processor indicated that the regression slope for Sustention(Voiced) scores with b = -7.19 was significantly greater than that for Sustention(Unvoiced) with b = -4.21, at the level a = .05. However, this contrast was not significant in the case of intelligibility scores for the PLPC processor. The contrast between regression slopes for Sustention Present and Sustention Absent intelligibility scores was not significant for either the LPC processor or the PLPC processor, suggesting that on the average the sustained and the abrupt consonants were equally vulnerable to the effects of bit errors.

Data for the Sibilation feature scores are presented in Appendix D. These distributions indicated that no significant difference in susceptibility to bit errors was present for the contrast between this feature being present and absent, or for the contrast between the voiced and unvoiced states of Sibilation, with either LPC or PLPC intelligibility scores.

Details of Graveness intelligibility scores are shown in Appendix E. The data analysis indicated that there was no significant difference in susceptibility to bit errors for the feature Graveness Present contrasted with Graveness Absent, for either the LPC or the PLPC processor scores. However, the LPC processor scores revealed a significant difference in regression slopes for Graveness(Voiced) with b = -5.26, in comparison with Graveness(Unvoiced) with b = -7.53, at the level a = .05. This contrast was not significant in the case of the distributions of scores for the PLPC processor; however, a similar bias was observed, i.e. the unvoiced state of Graveness displayed a greater susceptibility to bit errors than the voiced state.

The distributions of intelligibility scores and other data for the Compactness intelligibility feature are presented in Appendix F. These scores showed a pattern similar to that obtained with the scores for Graveness, in that the unvoiced state of the feature exhibited a greater vulnerability to bit errors than the voiced state, in the case of scores for both the LPC and the PLPC processors. However, as with the Graveness feature, the contrast was significant for the LPC processor scores (a = .05) but not significant for the PLPC processor. The contrast between Compactness Present and Compactness Absent regression slopes was not significant for either processor.

7.2. Implications for Digital Voice Terminal Hardware Development.

The magnitude of improvement in speech intelligibility obtained by using the piecewise linear predictive coding method in preference to conventional LPC is sufficiently small that it would be difficult to justify choosing PLPC hardware and software for a voice terminal design if there were premium hardware costs incurred by using PLPC rather than LPC. However, the nature of the PLPC algorithm is such that a voice terminal based on this approach could reasonably be expected to cost less, not more, than an LPC design. The basis for this conclusion is that the PLPC algorithm operates at half the sample rate of LPC, for performing the speech analysis and synthesis functions. The PLPC algorithm also requires less computation: fewer multiplications and fewer additions, than conventional LPC (this is assuming that the filtering operations at the input and output are done with hardware filters or with CCD, rather than by digital filtering operations). Inevitably these factors should cause a PLPC-based voice terminal to be cheaper and/or more cost effective than an LPC-based design. For example, the reduced computational load would free up computational capacity in the processor to be available for modem functions, signalling and supervision, error correction and detection, acoustic noise reduction algorithms, etc.

These advantages would carry over to a wideband version of PLPC operating at 8.0 or 9.6 Kbps, with a residual (error) signal representing the difference between the linear predictive model and the actual speech signal measured and encoded for transmission along with the narrowband data. In this context the reduced sample rate made possible by the piecewise-LPC configuration would reduce the computational load involved in calculating residuals, as well as permitting more data bits to be assigned in encoding the residuals in comparison with alternative methods. Thus a multiple rate processor (MRP) voice terminal design based on PLPC can be expected to offer performance advantages as well as computational advantages in comparison with other approaches.

With regard to vulnerability to bit errors, a variety of coding refinements are possible that can alleviate this problem, ranging from simple rearrangement of the bit pattern per data frame, to sophisticated error detection and correction schemes. These tests were made without any refinements of this nature. However, they indicate that coding refinements to reduce susceptibility to bit errors should always provide greater benefit for the PLPC algorithm than they can provide with conventional LPC, because of the intrinsic advantages that are possessed by the PLPC technique: more accurate

modeling of the speech signal, and inherent redundancy provided by the PLPC technique.

7.3. Implications for Intelligibility Test and Evaluation Procedures and Standards.

The regression slopes calculated for different speaker's intelligibility scores showed significant differences among the speakers, suggesting that there are innate differences in individual speaker's susceptibilities to bit error effects. The trend tended to follow the relative intelligibility rank possessed by individual speaker's intelligibility scores under ideal conditions (no bit errors), suggesting that some speakers speech signals have intrinsic properties causing them to be more susceptible to signal degradation in general, whether caused by effects of bit errors on the data signals, or by a reduced number of data coefficients, etc. This question deserves further study, since a better understanding of the causes of speaker variability might lead to improvements in the voice processing algorithms to meet the goal of obtaining fully adequate performance with a large and varied population of speakers.

Since the values of the independent variable (bit error rate) were equal in each speaker test, the overall regression equations (all speakers) involved values of the slope and elevation that were the average values of the slopes and elevations respectively, of individual speakers. The reasons for this are discussed in Appendix I.1.

The analysis of variance findings showed that highly significant differences among intelligibility scores for individual speakers were present, as well as significant interactions between speakers and processors, as well as speakers and bit error rates. Conspicuous evidence of these interactions is revealed in comparing the regression lines derived from the LPC and the PLPC performance data with speakers LL and PK, for example (Figs. 5 and 9).

The degree of speaker variability and speaker/processor interactions suggests that inadequate attention has been given to this topic. While these effects have been commonplace in speech testing over the past several years, they have received little attention, in part because of the practice of calculating standard errors from listener mean scores only.

The economics of speech testing would rule against routine testing with a large number of speakers. However, if the purpose of test and evaluation is to guide critical decisions in comparing the performance of alternative processors, to evaluate the significance of improvements in the speech processing algorithms, or to predict the performance that can be expected with a large and varied population of speakers, it is likely that the present practice of testing with six (male) speakers is marginal, and that a reevaluation should be made as to an appropriate number and types of speakers to be used in speech testing in order to fully meet these objectives.

For the near-term, it would seem desirable to double the number of speakers as a minimum, where critical tests are required. With twelve speakers, the idiosyncrasies of individual speakers would tend to be averaged out in the data population, a result particularly valuable in regard to the data for the individual intelligibility features. Since it is in these fine details that the significance differences between different processors are found, the proposed change should be of considerable value not only for comparing processors, but for clearly identifying the intelligibility features that are most deficient and where refinements could bring the greatest benefits.

With regard to further testing in order to assess effects of bit errors on speech intelligibility, tests with processors that incorporate special coding provisions to reduce vulnerability to bit errors should include test conditions at 10% and 20% bit error rates in addition to those reported here. Tests at these six rates would result in a mean bit error rate of 6.5% (compared with 2.25% in these tests). The confidence limits associated with regression models have the property of widening above and below the mean value (see Appendix I.1); the additional rates would give the tightest confidence limits for predicting scores in the range from about 5% to 8% bit error rate.

It would be desirable to conduct further tests of bit error conditions with two replications of each processing condition (Note: replications of processing, as opposed to replication of the presentation to listeners). Such a procedure would permit a better assessment of variations caused by the algorithm or process used to generate the bit errors.

8.0 CONCLUSIONS AND RECOMMENDATIONS.

Formal tests and evaluations were conducted to compare the susceptibility of narrowband linear predictive coding (LPC) for voice processing, and the more recent innovation of piecewise linear predictive coding (PLPC) to the effects of bit errors, both processor configurations operating at a 2400 bit-per-second data rate. Test results confirmed an hypothesis that piecewise LPC voice processors are less susceptible to bit errors than conventional LPC.

Significant differences were found in the susceptibilities of individual speakers and individual intelligibility features to the effects of bit errors.

Linear regression models were utilized in constructing tables predicting intelligibility performance, and approximate confidence limits for the predictions, over a range of bit error rates. These tables include interpolation and extrapolation for estimating intelligibility performance that might be obtained under specified bit error conditions.

The findings suggest that the piecewise version of linear predictive coding for narrowband digital voice communications offers a superior alternative to conventional linear predictive coding (LPC), since these benefits are obtained simultaneously with a relaxation of hardware implementation requirements for speed and number of computations.

The piecewise linear predictive coding (PLPC) processor was shown to consistently give better intelligibility than LPC, both under "ideal" conditions and under bit error conditions.

Further improvement in the piecewise-LPC voice processor performance is foreseen with minor refinements of the frequency band arrangement, and the parameter coding tables used in PLPC.

These benefits are foreseen to carry over to a medium bandwidth configuration of piecewise-LPC operating at 8.0 or 9.6 kilobits per second, adding a residual signal for improved speech quality and naturalness and tolerance to acoustic noise environments.

It is recommended that the research and development on piecewise linear predictive coding be accelerated to completion of the optimization of performance of the narrowband version, and

to include investigations and implementation of a feasibility model operating at 8.0 and 9.6 kilobits per second in addition to the narrowband configuration. The investigation should also address the feasibility of embedding the 2400 bit-per-second data stream in the data stream at the higher data rates.

BIBLIOGRAPHY

1. B.S.Atal and S.L.Hanauer, "Speech analysis and synthesis by linear prediction of the speech wave," Jour.Acous.Soc.Am. 50 No.2 (Part 2), 1971.

2. W.J.Conover, Practical Nonparametric Statistics, John Wiley & Sons, NY (1971).

3. G. Fant, Acoustic Theory of Speech Production, Mouton & Co., 's-Gravenhage, 1960.

4. J.E.Roberts and R.H.Wiggins, "Piecewise linear predictive coding (PLPC)," Conf.Record, 1976 IEEE Intl.Conference on Acous., Speech and Signal Processing, IEEE Cat.No.76CH1067-8 ASSP, 470-473, Apr 1976.

5. J. Makhoul, "Linear prediction: a tutorial review," Proc. IEEE 63, 561-580, Apr 1975.

6. H. Scheffe, The Analysis of Variance, John Wiley & Sons, New York (1959).

7. G.W. Snedecor and W.G.Cochran, Statistical Methods (6th Ed.), Iowa State University Press (1967).

8. W.D.Voiers, A.D.Sharpley and C.J.Hehmsoth, "Research on diagnostic evaluation of speech intelligibility," AFCRL-72-0694, Jan. 1973.

9. B.J.Winer, Statistical Principles in Experimental Design, (2d Ed.), McGraw-Hill Book Co., New York (1971).

10. R. Jakobson, C.G.Fant and M. Halle, Preliminaries to Speech Analysis: The Distinctive Features and Their Correlates. MIT Press, Cambridge, Mass. (1969).

INTELLIGIBILITY FEATURE: *VOICING*

Test Items for *VOICING (Frictional)*

Voicing Feature - Present		Voicing Feature - Absent
VEAL	—	FEEL
GIN	—	CHIN
ZED	—	SAID
VAST	—	FAST
VAULT	—	FAULT
JOCK	—	CHOCK
VOLE	—	FOAL
ZOO	—	SUE

Test Items for *VOICING (Non - Frictional)*

Voicing Feature - Present		Voicing Feature - Absent
BEAN	—	PEEN
DINT	—	TINT
DENSE	—	TENSE
GAFF	—	CALF
DAUNT	—	TAUNT
BOND	—	POND
GOAT	—	COAT
DUNE	—	TUNE

A.1. DRT test words for Voicing.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors: Intelligibility Scores for VOICING.

Nr. of rows ("A" 's): [Processor Modes: LPC and PLPC, at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"):[Scores for four VOICING states, x 2 presentations] 8= M

Values by rows:

	VOICING PRESENT		VOICING ABSENT	
	Frictional	Non-Frictional	Frictional	Non-Frictional
LPC at 2400 BPS.				
Zero bit error rate. Test #2050.				
Speaker LL	93.75	90.62	100.00	96.87
	93.75	96.87	100.00	100.00
Speaker RH	96.87	96.87	96.87	100.00
	100.00	100.00	93.75	96.87
Speaker CH	96.87	100.00	100.00	100.00
	100.00	100.00	96.87	100.00
Speaker PK	59.37	100.00	100.00	100.00
	62.50	100.00	90.62	100.00
Speaker JE	71.87	93.75	81.25	100.00
	87.50	96.87	75.00	100.00
Speaker BV	96.87	100.00	90.62	96.87
	100.00	100.00	87.50	96.87
1% bit error rate. Test #2051.				
Speaker LL	87.50	90.62	100.00	100.00
	87.50	84.37	93.75	100.00
Speaker RH	96.87	100.00	81.25	96.87
	96.87	96.87	87.50	93.75
Speaker CH	100.00	100.00	100.00	96.87
	100.00	100.00	96.87	96.87
Speaker PK	53.12	87.50	81.25	96.87
	65.62	100.00	84.37	100.00
Speaker JE	46.87	78.12	78.12	100.00
	68.75	84.37	68.75	100.00
Speaker BV	90.62	100.00	84.37	96.87
	96.87	100.00	84.37	93.75

A.2. Data Table: Voicing Intelligibility Scores for LPC and PLPC.

	VOICING PRESENT		VOICING ABSENT	
	Frictional	Non-Frictional	Frictional	Non-Frictional
LPC at 2400 BPS - continued.				
3% bit error rate. Test #2052.				
Speaker LL	65.62	59.37	84.37	84.37
	68.75	50.00	84.37	84.37
Speaker RH	90.62	100.00	96.87	87.50
	93.75	100.00	90.62	81.25
Speaker CH	100.00	100.00	81.25	93.75
	100.00	96.87	81.25	100.00
Speaker PK	71.87	78.12	84.37	81.25
	68.75	84.37	87.50	81.25
Speaker JE	62.50	31.25	84.37	84.37
	56.25	34.37	90.62	90.62
Speaker BV	81.25	100.00	50.00	71.87
	78.12	100.00	78.12	75.00
5% bit error rate. Test #2053.				
Speaker LL	68.75	43.75	62.50	65.62
	71.87	43.75	56.25	68.75
Speaker RH	90.62	100.00	37.50	84.37
	100.00	100.00	50.00	90.62
Speaker CH	87.50	93.75	71.87	90.62
	96.87	100.00	62.50	90.62
Speaker PK	28.12	28.12	71.87	96.87
	25.00	37.50	81.25	96.87
Speaker JE	71.87	-21.87	62.50	96.87
	71.87	-21.87	81.25	96.87
Speaker BV	65.62	96.87	50.00	78.12
	71.87	93.75	68.75	68.75
PLPC at 2400 BPS.				
Zero bit error rate. Test #2043.				
Speaker LL	100.00	100.00	93.75	78.12
	100.00	100.00	90.62	90.62
Speaker RH	100.00	100.00	87.50	96.87
	100.00	100.00	93.75	100.00
Speaker CH	100.00	100.00	96.87	100.00
	100.00	100.00	90.62	100.00
Speaker PK	75.00	100.00	93.75	100.00
	81.25	100.00	93.75	100.00
Speaker JE	90.62	96.87	100.00	100.00
	100.00	96.87	96.87	100.00
Speaker BV	93.75	100.00	87.50	87.50
	96.87	100.00	84.37	87.50

A.2.-continued (part 2).

	VOICING PRESENT		VOICING ABSENT	
	Frictional	Non-Frictional	Frictional	Non-Frictional
PLPC at 2400 BPS - continued.				
1% bit error rate. Test #2047.				
Speaker LL	96.87	96.87	87.50	100.00
	100.00	93.75	81.25	96.87
Speaker RH	100.00	100.00	100.00	100.00
	96.87	100.00	93.75	100.00
Speaker CH	100.00	100.00	100.00	100.00
	100.00	100.00	100.00	100.00
Speaker PK	56.25	100.00	87.50	100.00
	71.87	93.75	84.37	100.00
Speaker JE	68.75	81.25	96.87	100.00
	84.37	81.25	90.62	100.00
Speaker BV	96.87	96.87	84.37	96.87
	100.00	100.00	71.87	87.50
3% bit error rate. Test #2048.				
Speaker LL	81.25	100.00	87.50	93.75
	84.37	100.00	68.75	87.50
Speaker RH	90.62	100.00	90.62	84.37
	93.75	100.00	87.50	87.50
Speaker CH	96.87	100.00	96.87	81.25
	100.00	100.00	100.00	81.25
Speaker PK	56.25	71.87	78.12	96.87
	59.37	68.75	68.75	93.75
Speaker JE	84.37	84.37	87.50	100.00
	96.87	90.62	75.00	87.50
Speaker BV	100.00	100.00	68.75	68.75
	96.87	100.00	71.87	56.25
5% bit error rate. Test #2049.				
Speaker LL	90.62	84.37	84.37	84.37
	96.87	84.37	81.25	78.12
Speaker RH	71.87	100.00	90.62	65.62
	87.50	100.00	81.25	62.50
Speaker CH	90.62	100.00	90.62	96.87
	100.00	100.00	78.12	87.50
Speaker PK	34.37	75.00	43.75	90.62
	65.62	75.00	31.25	84.37
Speaker JE	81.25	87.50	43.75	53.12
	93.75	90.62	31.25	56.25
Speaker BV	100.00	100.00	75.00	28.12
	96.87	100.00	62.50	28.12

A.2.-continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors: Intelligibility Scores for VOICING.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	7	4000.99829	571.57118		
"A" 's (pro cessors)	1	1937.61525	1937.61525	8.85945 **	(p=.9969)
"B" 's (speakers)	5	15455.87111	3091.17422	14.13393 ***	(p=.9999)
"C" 's (BER's)	3	26663.44256	8887.81418	40.63821 ***	(p=.9999)
AB Interactions	5	2552.46438	510.49287	2.33415 *	(p=.9558)
AC interactions	3	697.06477	232.35492	1.06240	(p=.5780)
BC Interactions	15	3795.98678	253.06578	1.15710	(p=.5379)
ABC interactions	15	2239.57060	149.30470	.68267	
Error	329	71954.20689	218.70579		
Total	383	129297.22063			

A.3J. Analysis of Variance Summary: Voicing (Total).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Intelligibility Scores for VOICING PRESENT.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio
Replications	3	1327.64794	442.54931	
"A" 's (processors)	1	5708.44036	5708.44036	41.43220*** (p=.9999)
"B" 's (speakers)	5	25948.60251	5189.72050	37.66730*** (p=.9999)
"C" 's (BER's)	3	9773.93434	3257.97811	23.64660*** (p=.9999)
AB Interactions	5	5993.84337	1198.76867	8.70073*** (p=.9999)
AC Interactions	3	2985.11859	995.03953	7.22205*** (p=.9998)
BC Interactions	15	6158.00864	410.53390	2.97967*** (p=.9996)
ABC Interactions	15	5034.53337	335.63555	2.43606 ** (p=.9964)
Error	141	19426.67719	137.77785	
Total	191	82356.80631		

A.3.2. Analysis of Variance Summary: Voicing Present.

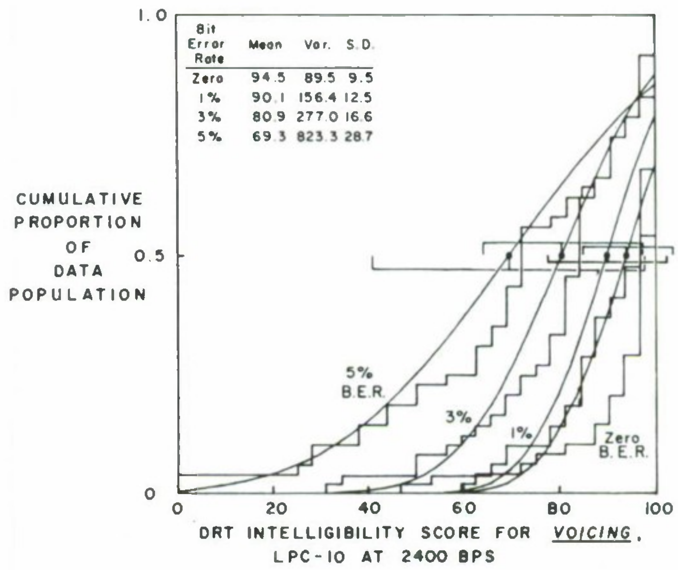
THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:

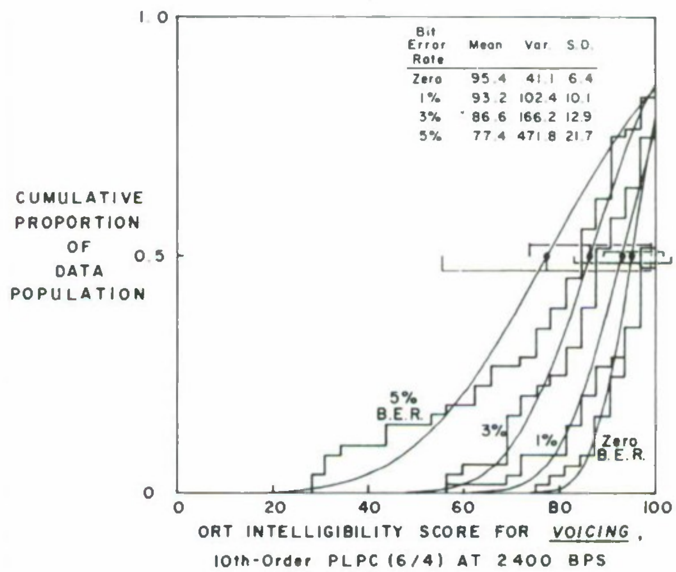
Intelligibility Scores for <u>VOICING ABSENT</u>.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	2614.72539	871.57513		
"A" 's (processors)	1	176.96640	176.96640	1.92857	(p=.8527)
"B" 's (speakers)	5	4901.07773	980.21554	10.68237 ***	(p=.9999)
"C" 's (BER's)	3	17753.34842	5917.78280	64.49191 ***	(p=.9999)
AB Interactions	5	862.61419	172.52283	1.88015	(p=.8900)
AC Interactions	3	538.21364	179.40454	1.95514	(p=.8708)
BC Interactions	15	1786.40319	119.09354	1.29787	(p=.7263)
ABC Interactions	15	5310.27043	354.01802	3.85808 ***	(p=.9999)
Error	141	12938.16994	91.76007		
Total	191	46881.78933			

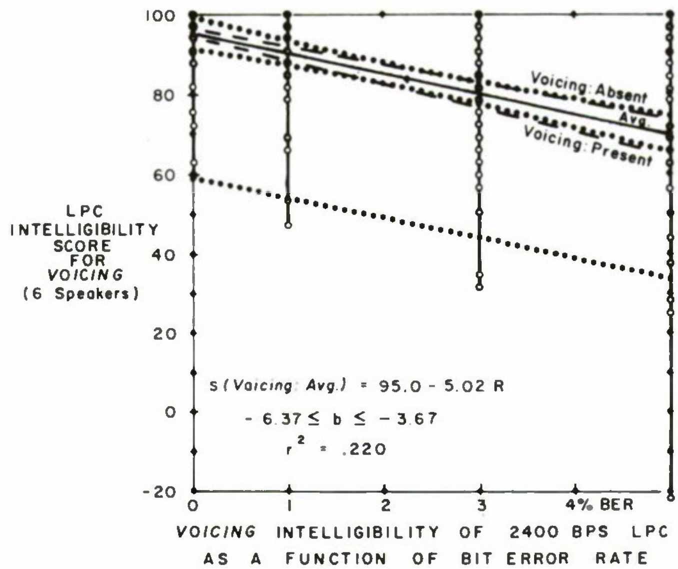
A.3.3. Analysis of Variance Summary: <u>Voicing Absent</u>.



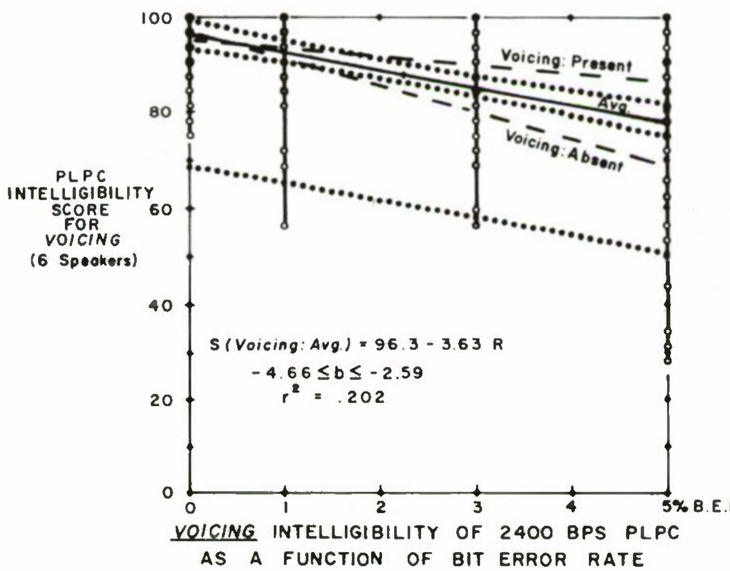
A.4.1. Cumulative distributions of the intelligibility scores for the Voicing feature, LPC-10 at 2400 BPS.



A.4.2. Cumulative distributions of the intelligibility scores for the Voicing feature, PLPC at 2400 BPS.



A.5.1. Scatter plot of scores, and linear regression model for the Voicing intelligibility feature, obtained with LPC-10 at 2400 BPS. Regression lines for Voicing-Present, and Voicing-Absent, are also shown.



A.5.2. Scatter plot of scores, and linear regression Model for the Voicing intelligibility feature, obtained with PLPC at 2400 BPS.

Intelligibility of *VOICING* vs. Bit Error Rate, for 2400 BPS LPC-10

Model: S(LPC) = 94.97 − 5.020(BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of *VOICING*		95% Confidence Limits: *Expected Avg Score*	95% Confidence Limits: *Individual Scores*
0	95.0		90.96 − 98.97	58.73 − 131.21
1	89.9		86.85 − 93.05	53.80 − 126.10
2	84.9		82.31 − 87.55	48.81 − 121.04
3	79.9		77.12 − 82.70	43.78 − 116.03
4	74.9		71.37 − 78.41	38.70 − 111.08
5	69.9		65.33 − 74.41	33.57 − 106.17
6	64.8		59.15 − 70.55	28.38 − 101.32
7	59.8	*Extrapolated*	52.89 − 66.76	23.15 − 96.51
8	54.8	*Values*	46.60 − 63.02	17.87 − 91.75
9	49.8		40.29 − 59.29	12.54 − 87.04
10%	44.8		33.96 − 55.58	7.17 − 82.37

A.6.1. Predicted intelligibility scores for Voicing, LPC-10 at 2400 BPS with bit errors (with no provisions for error protection).

Intelligibility of *Voicing* vs. Bit Error Rate, for 2400 BPS PLPC

Model: S(PLPC) = 96.32 − 3.625(BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of *Voicing*		95% Confidence Limits: *Expected Avg Score*	95% Confidence Limits: *Individual Scores*
0	96.3		93.27 ↔ 99.38	68.67 ↔ 123.97
1	92.7		90.33 ↔ 95.06	65.12 ↔ 120.28
2	89.1		87.07 ↔ 91.07	61.52 ↔ 116.62
3	85.4		83.32 ↔ 87.58	57.88 ↔ 113.01
4	81.8		79.14 ↔ 84.50	54.21 ↔ 109.43
5	78.2		74.73 ↔ 81.66	50.50 ↔ 105.89
6	74.6		70.22 ↔ 78.92	46.75 ↔ 102.39
7	70.9	*Extrapolated*	65.66 ↔ 76.24	42.96 ↔ 98.93
8	67.3	*Values*	61.06 ↔ 73.58	39.14 ↔ 95.51
9	63.7		56.45 ↔ 70.94	35.28 ↔ 92.12
10%	60.1		51.83 ↔ 68.32	31.38 ↔ 88.76

A.6.2. Predicted intelligibility scores for Voicing, PLPC at 2400 BPS with bit errors (with no provisions for error protection).

INTELLIGIBILITY FEATURE: *NASALITY*

Test Items for *NASALITY (Grave)*

Nasality Feature - Present		Nasality Feature - Absent
MEET	—	BEET
MIT	—	BIT
MEND	—	BEND
MAD	—	BAD
MOM	—	BOMB
MOSS	—	BOSS
MOAN	—	BONE
MOOT	—	BOOT

Test Items for *NASALITY (Acute)*

Nasality Feature - Present		Nasality Feature - Absent
NEED	—	DEED
NIP	—	DIP
NECK	—	DECK
NAB	—	DAB
KNOCK	—	DOCK
GNAW	—	DAW
NOTE	—	DOTE
NEWS	—	DUES

B.I. DRT test words for Nasality.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors: Intelligibility Scores for NASALITY.

Nr. of rows ("A" 's): [Processor Modes: LPC and PLPC, at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"):[Four NASALITY states, x 2 presentations] 8= M

Values by rows: NASALITY PRESENT NASALITY ABSENT

	NASALITY PRESENT Grave	NASALITY PRESENT Acute	NASALITY ABSENT Grave	NASALITY ABSENT Acute
LPC at 2400 BPS.				
Zero bit error rate. Test #2050.				
Speaker LL	100.00	100.00	96.87	100.00
	100.00	100.00	96.87	100.00
Speaker RH	96.87	100.00	100.00	100.00
	96.87	100.00	100.00	96.87
Speaker CH	100.00	100.00	100.00	100.00
	96.87	100.00	96.87	93.75
Speaker PK	100.00	100.00	100.00	100.00
	100.00	100.00	100.00	100.00
Speaker JE	84.37	100.00	84.37	84.37
	81.25	100.00	81.25	87.50
Speaker BV	96.87	100.00	96.87	100.00
	96.87	100.00	100.00	90.62
1% bit error rate. Test #2051.				
Speaker LL	100.00	100.00	90.62	96.87
	100.00	100.00	96.87	90.62
Speaker RH	96.87	100.00	93.75	93.75
	96.87	100.00	90.62	96.87
Speaker CH	100.00	100.00	100.00	96.87
	93.75	96.87	93.75	96.87
Speaker PK	96.87	100.00	87.50	93.75
	100.00	100.00	96.87	100.00
Speaker JE	75.00	93.75	93.75	96.87
	78.12	100.00	90.62	93.75
Speaker BV	87.50	93.75	96.87	100.00
	93.75	100.00	100.00	93.75

B.2. Data Table: Nasality Intelligibility Scores for LPC and PLPC.

	NASALITY PRESENT		NASALITY ABSENT	
	Grave	Acute	Grave	Acute
(LPC at 2400 BPS)				
3% bit error rate. Test #2052.				
Speaker LL	93.75	93.75	100.00	93.75
	100.00	100.00	100.00	93.75
Speaker RH	93.75	100.00	93.75	78.12
	93.75	100.00	90.62	62.50
Speaker CH	100.00	100.00	93.75	96.87
	100.00	96.87	87.50	75.00
Speaker PK	78.12	78.12	90.62	90.62
	90.62	75.00	84.37	84.37
Speaker JE	59.37	100.00	87.50	100.00
	62.50	100.00	78.12	100.00
Speaker BV	65.62	93.75	90.62	96.87
	87.50	96.87	96.87	96.87
5% bit error rate. Test #2053.				
Speaker LL	87.50	78.12	93.75	90.62
	96.87	87.50	87.50	87.50
Speaker RH	71.87	90.62	53.12	87.50
	90.62	96.87	31.25	71.87
Speaker CH	100.00	96.87	78.12	43.75
	100.00	100.00	90.62	40.62
Speaker PK	65.62	62.50	90.62	87.50
	65.62	62.50	81.25	90.62
Speaker JE	43.75	81.25	87.50	90.62
	40.62	90.62	78.12	87.50
Speaker BV	56.25	81.25	84.37	81.25
	62.50	84.37	75.00	68.75
PLPC at 2400 BPS.				
Zero bit error rate. Test #2043.				
Speaker LL	100.00	100.00	100.00	96.87
	100.00	100.00	100.00	100.00
Speaker RH	96.87	100.00	96.87	87.50
	100.00	100.00	93.75	78.12
Speaker CH	100.00	100.00	100.00	93.75
	100.00	100.00	96.87	93.75
Speaker PK	100.00	100.00	100.00	100.00
	100.00	100.00	100.00	100.00
Speaker JE	87.50	96.87	100.00	100.00
	93.75	100.00	100.00	100.00
Speaker BV	75.00	100.00	96.87	93.75
	87.50	100.00	100.00	100.00

B.2.-continued (part 2).

	NASALITY PRESENT		NASALITY ABSENT	
	Grave	Acute	Grave	Acute
(PLPC at 2400 BPS)				
1% bit error rate. Test #2047.				
Speaker LL	90.62	100.00	100.00	100.00
	100.00	100.00	90.62	100.00
Speaker RH	100.00	100.00	93.75	93.75
	100.00	100.00	100.00	90.62
Speaker CH	100.00	100.00	81.25	90.62
	100.00	100.00	81.25	96.87
Speaker PK	100.00	96.87	100.00	96.87
	100.00	100.00	100.00	100.00
Speaker JE	90.62	100.00	96.87	100.00
	93.75	100.00	96.87	96.87
Speaker BV	90.62	93.75	93.75	87.50
	96.87	81.25	96.87	93.75
3% bit error rate. Test #2048.				
Speaker LL	71.87	81.25	68.75	93.75
	90.62	96.87	65.62	100.00
Speaker RH	100.00	100.00	71.87	78.12
	100.00	100.00	71.87	75.00
Speaker CH	87.50	100.00	53.12	87.50
	90.62	100.00	43.75	78.12
Speaker PK	90.62	87.50	96.87	96.87
	96.87	100.00	93.75	100.00
Speaker JE	90.62	100.00	87.50	100.00
	93.75	100.00	96.87	100.00
Speaker BV	93.75	62.50	84.37	75.00
	100.00	81.25	90.62	62.50
5% bit error rate. Test #2049.				
Speaker LL	75.00	71.87	81.25	96.87
	93.75	81.25	84.37	96.87
Speaker RH	96.87	84.37	84.37	75.00
	100.00	96.87	84.37	75.00
Speaker CH	96.87	100.00	46.87	50.00
	96.87	100.00	56.25	40.62
Speaker PK	71.87	68.75	68.75	84.37
	71.87	87.50	71.87	81.25
Speaker JE	65.62	100.00	78.12	84.37
	75.00	96.87	65.62	81.25
Speaker BV	78.12	65.62	96.87	59.37
	90.62	71.87	100.00	50.00

B.2.-continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and FLPC Inrelligibiliry Scores ar 2400 BPS wirh bir errors:
Inrelligibiliry Scores for NASALITY.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F rario	
Replicarions	7	2895.24552	413.60650		
"A" 's (processors)	1	.91259	.91259	.00818	
"B" 's (speakers)	5	1259.29004	251.85800	2.25619	(p=.9488)
"C" 's (BER's)	3	19854.90116	6618.30038	59.34064***	(p=.9999)
AB Inreracrions	5	2364.87845	472.97569	4.24076***	(p=.9990)
AC Inreracrions	3	259.87194	86.62398	.77668	
BC Inreracrions	15	1414.76412	94.31760	.84566	
ABC Inreracrions	15	2045.13405	136.34227	1.22246	(p=.6474)
Error	329	36693.58053	111.53063		
Toral	383	66788.57840			

B.3.1. Analysis of Variance Summary: Nasality (Total).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Inrelligibiliry Scores ar 2400 BPS with bir errors:

Inrelligibiliry Scores for NASALITY PRESENT.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replicarions	3	1572.20025	524.06675		
"A" 's (processors)	1	249.24967	249.24967	3.97173*	(p=.9541)
"B" 's (speakers)	5	4371.36623	874.27324	13.93135***	(p=.9999)
"C" 's (BER's)	3	7484.43923	2494.81307	39.75431***	(p=.9999)
AB Inreracrions	5	1545.36168	309.07233	4.92500***	(p=.9997)
AC Inreracrions	3	270.69956	90.23318	1.43784	(p=.7463)
BC Inreracrions	15	2953.26408	196.88427	3.13730***	(p=.9998)
ABC Inreracrions	15	808.37282	53.89152	.85874	
Error	141	8848.56605	62.75578		
Toral	191	28103.51957			

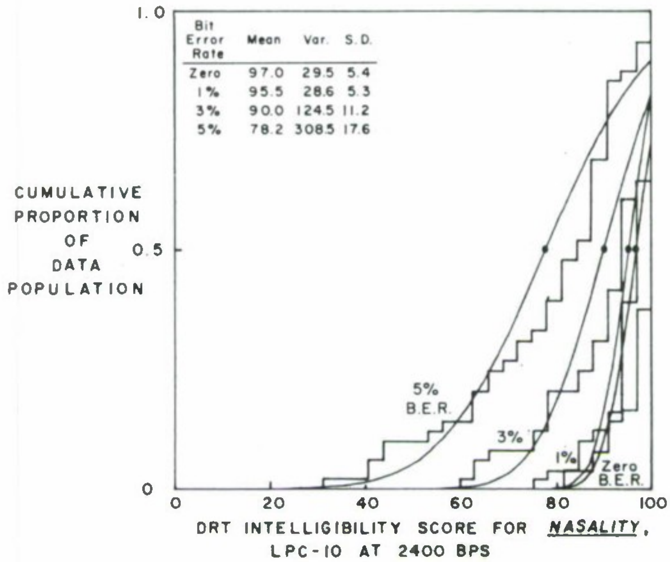
B.3.2. Analysis of Variance Summary: Nasality Present.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

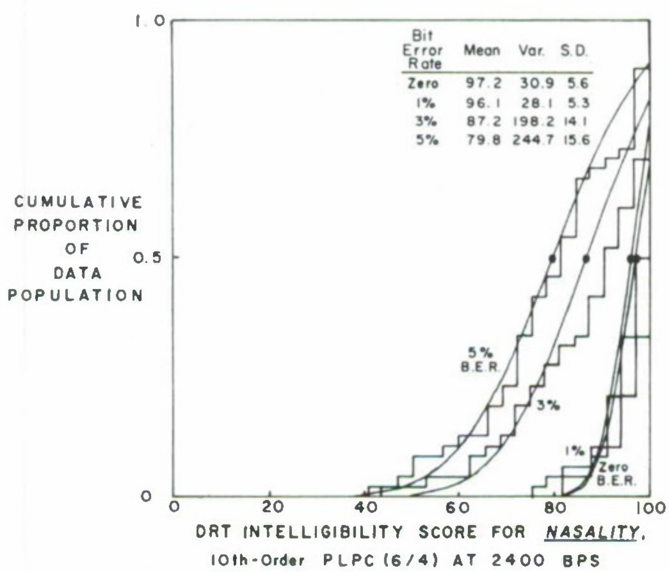
Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors: Intelligibility Scores for NASALITY ABSENT.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	222.37860	74.12620		
"A" 's (processors)	1	293.73308	293.73308	3.59198	(p=.9432)
"B" 's (speakers)	5	4241.30990	848.26198	10.37316***	(p=.9999)
"C" 's (BER's)	3	12771.98084	4257.32694	52.06170***	(p=.9999)
AB Interactions	5	1299.83236	259.96647	3.17905**	(p=.9903)
AC Interactions	3	563.21355	187.73785	2.29579	(p=.9169)
BC Interactions	15	3881.60039	258.77335	3.16446***	(p=.9998)
ABC Interactions	15	2780.11956	185.34130	2.26648**	(p=.9929)
Error	141	11530.22385	81.77463		
Total	191	37584.39213			

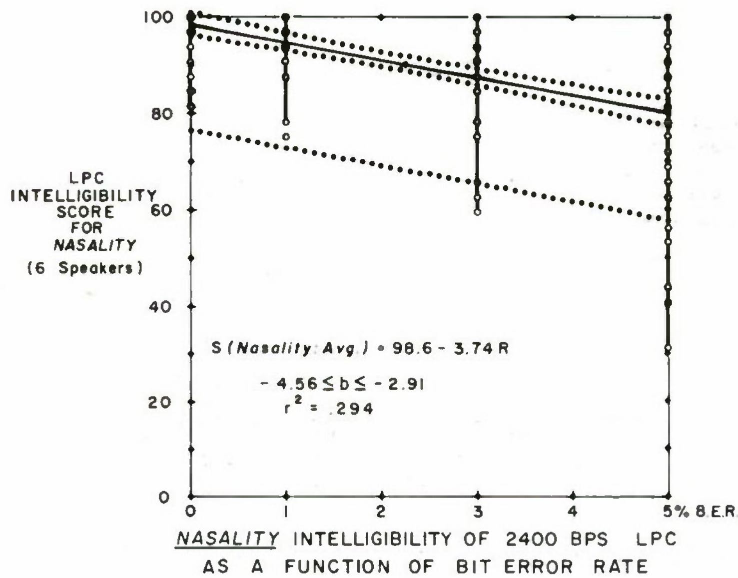
B.3.3. Analysis of Variance Summary: Nasality Absent.



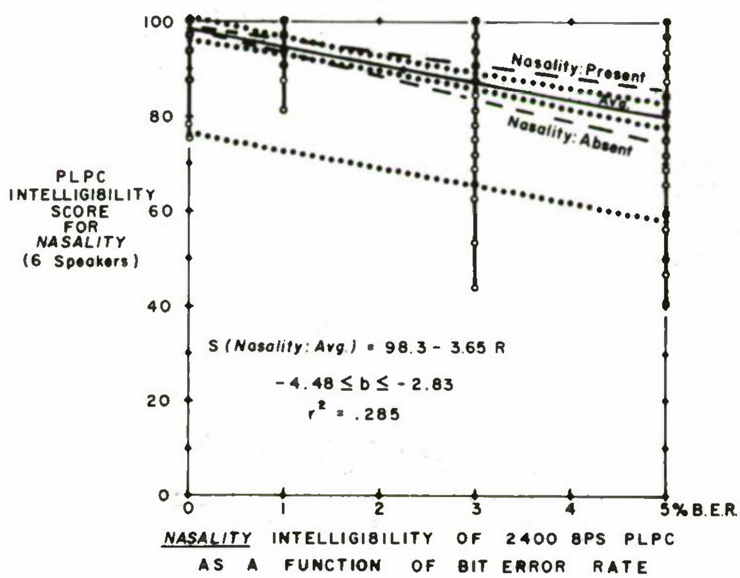
B.4.1. Cumulative distributions of the intelligibility scores for the Nasality feature, LPC-10 at 2400 BPS.



B.4.2. Cumulative distributions of the Intelligibility scores for the Nasality feature, PLPC at 2400 BPS.



B.5.1. Scatter plot of scores, and linear regression model for the Nasality intelligibility feature, obtained with LPC-10 at 2400 BPS.



B.5.2. Scatter plot of scores, and linear regression model for the Nasality intelligibility feature, obtained with PLPC at 2400 BPS. Regression lines for Nasality-Present and Nasality-Absent, are also shown.

Intelligibility of NASALITY vs Bit Error Rate, for 2400 BPS LPC-10

Model: S(LPC) = 98.59 - 3.735 (BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of NASALITY		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	98.6		96.14 - 101.04	76.42 - 120.76
1	94.9		92.96 - 96.75	72.74 - 116.97
2	91.1		89.51 - 92.72	69.02 - 113.21
3	87.4		85.67 - 89.09	65.28 - 109.48
4	83.6		81.50 - 85.80	61.51 - 105.79
5	79.9		77.13 - 82.69	57.70 - 102.12
6	76.2	↓	72.69 - 79.66	53.87 - 98.49
7	72.4	Extrapolated	68.20 - 76.68	50.00 - 94.88
8	68.7	Values	63.68 - 73.73	46.10 - 91.31
9	65.0		59.16 - 70.78	42.18 - 87.76
10%	61.2		54.62 - 67.85	38.23 - 84.24

B.6.1. Predicted intelligibility scores for Nasality, LPC-10 at 2400 BPS with bit errors (with no provisions for error protection).

Intelligibility of Nasality vs Bit Error Rate, for 2400 BPS PLPC

Model: S(PLPC) = 98.31 - 3.654 (BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of Nasality		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	98.3		95.86 ↔ 100.76	76.12 ↔ 120.50
1	94.7		92.75 ↔ 96.55	72.52 ↔ 116.79
2	91.0		89.39 ↔ 92.60	68.89 ↔ 113.11
3	87.3		85.64 ↔ 89.05	65.23 ↔ 109.46
4	83.7		81.54 ↔ 85.85	61.53 ↔ 105.85
5	80.0		77.26 ↔ 82.82	57.81 ↔ 102.27
6	76.4	↓	72.89 ↔ 79.88	54.06 ↔ 98.71
7	72.7	Extrapolated	68.48 ↔ 76.98	50.27 ↔ 95.19
8	69.1	Values	64.05 ↔ 74.10	46.46 ↔ 91.69
9	65.4		59.61 ↔ 71.24	42.61 ↔ 88.23
10%	61.8		55.15 ↔ 68.39	38.74 ↔ 84.79

B.6.2. Predicted intelligibility scores for Nasality, PLPC at 2400 BPS with bit errors (with no provisions for error protection).

INTELLIGIBILITY FEATURE: *SUSTENTION*

Test Items for *SUSTENTION (Voiced)*

Sustention Feature - Present		Sustention Feature - Absent
VEE	—	BEE
VILL	—	BILL
THEN	—	DEN
THAN	—	DAN
VOX	—	BOX
VON	—	BON
THOUGH	—	DOUGH
THOSE	—	DOZE

Test Items for *SUSTENTION (Unvoiced)*

Sustention Feature - Present		Sustention Feature - Absent
SHEET	—	CHEAT
THICK	—	TICK
FENCE	—	PENCE
SHAD	—	CHAD
THONG	—	TONG
SHAW	—	CHAW
FOO	—	POOH
SHOES	—	CHOOSE

C.I. DRT test words for Sustention.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC intelligibility scores at 2400 BPS with bit errors: Scores for <u>SUSTENTION</u> feature.

Nr. of rows ("A" 's): [Processor Modes: LPC and PLPC at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"): [Four states of SUSTENTION x 2 presentations] 8= M

Values by rows:	SUSTENTION PRESENT		SUSTENTION ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
LPC at 2400 BPS.				
Zero bit error rate. Test #2050.				
Speaker LL	84.37	96.87	68.75	84.37
	71.87	96.87	71.87	81.25
Speaker RH	100.00	100.00	93.75	100.00
	96.87	96.87	96.87	100.00
Speaker CH	93.75	71.87	84.37	100.00
	93.75	71.87	84.37	96.87
Speaker PK	93.75	100.00	59.37	100.00
	87.50	96.87	62.50	96.87
Speaker JE	78.12	96.87	46.87	90.62
	78.12	90.62	65.62	93.75
Speaker BV	78.12	96.87	96.87	71.87
	75.00	93.75	96.87	65.62
1% bit error rate. Test #2051.				
Speaker LL	65.62	87.50	34.37	62.50
	65.62	71.87	50.00	68.75
Speaker RH	96.87	87.50	100.00	96.87
	93.75	78.12	93.75	100.00
Speaker CH	100.00	43.75	75.00	81.25
	100.00	50.00	84.37	87.50
Speaker PK	71.87	96.87	40.62	96.87
	62.50	87.50	53.12	100.00
Speaker JE	78.12	56.25	34.37	96.87
	81.25	62.50	62.50	100.00
Speaker BV	84.37	78.12	90.62	62.50
	65.62	87.50	84.37	68.75

C.2. Data Table: <u>Sustention</u> Intelligibility Scores for LPC and PLPC.

	SUSTENTION PRESENT		SUSTENTION ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
LPC at 2400 BPS - continued.				
3% bit error rate. Test #2052.				
Speaker LL	43.75	93.75	65.62	53.12
	46.87	90.62	71.87	62.50
Speaker RH	84.37	87.50	50.00	87.50
	87.50	87.50	62.50	75.00
Speaker CH	75.00	46.87	37.50	90.62
	78.12	65.62	34.37	96.87
Speaker PK	37.50	75.00	18.75	71.87
	40.62	78.12	15.62	84.37
Speaker JE	18.75	50.00	18.75	75.00
	25.00	62.50	21.87	84.37
Speaker BV	75.00	81.25	71.87	53.12
	71.87	81.25	75.00	50.00
5% bit error rate. Test #2053.				
Speaker LL	3.12	87.50	59.37	71.87
	12.50	90.62	59.37	78.12
Speaker RH	78.12	78.12	65.62	81.25
	93.75	75.00	59.37	65.62
Speaker CH	53.12	43.75	50.00	81.25
	68.75	40.62	43.75	62.50
Speaker PK	56.25	37.50	46.87	81.25
	53.12	28.12	25.00	68.75
Speaker JE	25.00	50.00	21.87	71.87
	37.50	65.62	34.37	65.62
Speaker BV	34.37	65.62	46.87	87.50
	46.87	62.50	71.87	90.62
PLPC at 2400 BPS.				
Zero bit error rate. Test #2043.				
Speaker LL	71.87	100.00	78.12	96.87
	75.00	96.87	87.50	87.50
Speaker RH	96.87	100.00	100.00	100.00
	96.87	100.00	100.00	100.00
Speaker CH	96.87	90.62	71.87	96.87
	96.87	84.37	71.87	96.87
Speaker PK	78.12	93.75	81.25	96.87
	65.62	93.75	84.37	100.00
Speaker JE	75.00	50.00	18.75	100.00
	65.62	50.00	34.37	93.75
Speaker BV	65.62	93.75	100.00	87.50
	71.87	84.37	100.00	84.37
1% bit error rate. Test #2047.				
Speaker LL	87.50	93.75	68.75	81.25
	96.87	93.75	68.75	90.62
Speaker RH	96.87	90.62	81.25	100.00
	100.00	90.62	93.75	100.00
(continued)				

C.2.-continued (part 2).

	SUSTENTION PRESENT		SUSTENTION ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
PLPC at 2400 BPS - continued.				
(1% bit error rate)				
Speaker CH	87.50	81.25	65.62	90.62
	93.75	84.37	71.87	96.87
Speaker PK	62.50	100.00	59.37	78.12
	68.75	87.50	75.00	71.87
Speaker JE	53.12	56.25	59.37	90.62
	40.62	25.00	78.12	93.75
Speaker BV	71.87	81.25	78.12	65.62
	59.37	87.50	81.25	68.75
3% bit error rate. Test #2048.				
Speaker LL	65.62	71.87	81.25	87.50
	90.62	59.37	78.12	78.12
Speaker RH	87.50	87.50	59.37	65.62
	78.12	87.50	56.25	71.87
Speaker CH	78.12	81.25	53.12	87.50
	75.00	81.25	62.50	81.25
Speaker PK	37.50	87.50	18.75	68.75
	50.00	84.37	-3.12	62.50
Speaker JE	50.00	15.62	65.62	81.25
	78.12	21.87	71.87	87.50
Speaker BV	71.87	59.37	84.37	68.75
	75.00	75.00	78.12	65.62
5% bit error rate. Test #2049.				
Speaker LL	75.00	75.00	46.87	81.25
	62.50	81.25	71.87	90.62
Speaker RH	78.12	84.37	68.75	65.62
	84.37	87.50	68.75	75.00
Speaker CH	100.00	71.87	46.87	71.87
	90.62	81.25	50.00	65.62
Speaker PK	12.50	46.87	65.62	59.37
	9.37	15.62	50.00	62.50
Speaker JE	37.50	21.87	34.37	62.50
	40.62	37.50	34.37	53.12
Speaker BV	65.62	59.37	46.87	53.12
	68.75	65.62	56.25	62.50

C.2.-continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC intelligibility scores at 2400 BPS with bit errors:

Scores for SUSTENTION feature.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	7	17754.74341	2536.39191		
"A" 's (processors)	1	423.25501	423.25501	1.70764	(p=.8355)
"B" 's (speakers)	5	29367.92969	5873.58593	23.69727***	(p=.9999)
"C" 's (BER's)	3	41122.09511	13707.36503	55.30304***	(p=.9999)
AB Interactions	5	4023.98893	804.79778	3.24699**	(p=.9927)
AC Interactions	3	609.08730	203.02910	.81913	
BC Interactions	15	5432.03123	362.13541	1.46105	(p=.8598)
ABC Interactions	15	3342.41413	222.82760	.89900	
Error	329	81545.66293	247.85915		
Total	383	183621.20774			

C.3.1. Analysis of Variance Summary: Sustention (Total).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC intelligibility scores at 2400 BPS with bit errors:

Scores for SUSTENTION(Voiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	2719.26864	906.42288		
"A" 's (processors)	1	1253.78963	1253.78963	6.43350 *	(p=.98801)
"B" 's (speakers)	5	30797.09503	6159.41900	31.60548 ***	(p=.99999)
"C" 's (BER's)	3	25076.11631	8358.70543	42.89056 ***	(p=.99999)
AB Interactions	5	2654.83785	530.96757	2.72452 *	(p=.97710)
AC Interactions	3	1956.08764	652.02921	3.34572 *	(p=.97865)
BC Interactions	15	6888.53757	459.23583	2.35645 **	(p=.99504)
ABC Interactions	15	5335.13854	355.67590	1.82506 *	(p=.96023)
Error	141	27478.71275	194.88448		
Total	191	104159.58400			

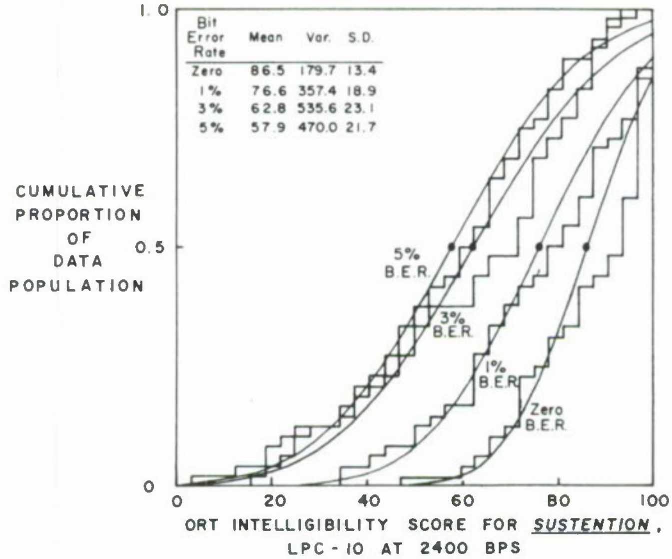
C.3.2. Analysis of Variance Summary: Sustention (Voiced).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

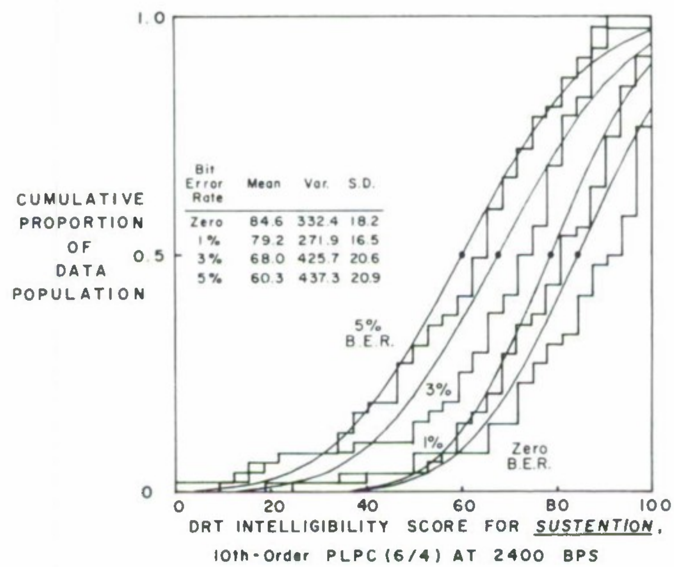
Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Scores for SUSTENTION(Unvoiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio		
Replications	3	1887.36492	629.12164			
"A" 's(processors)	1	39.86719	39.86719	.19983		
"B" 's(speakers)	5	7901.14748	1580.22949	7.92104	***	(p=.9999)
"C" 's (BER's)	3	16949.60582	5649.86860	28.32047	***	(p=.9999)
AB Interactions	5	4216.37111	843.27422	4.22698	**	(p=.9987)
AC Interactions	3	432.50067	144.16689	.72264		
BC Interactions	15	5557.97827	370.53188	1.85732	*	(p=.9648)
ABC Interactions	15	1199.50342	79.96689	.40084		
Error	141	28129.17501	199.49769			
Total	191	66313.51389				

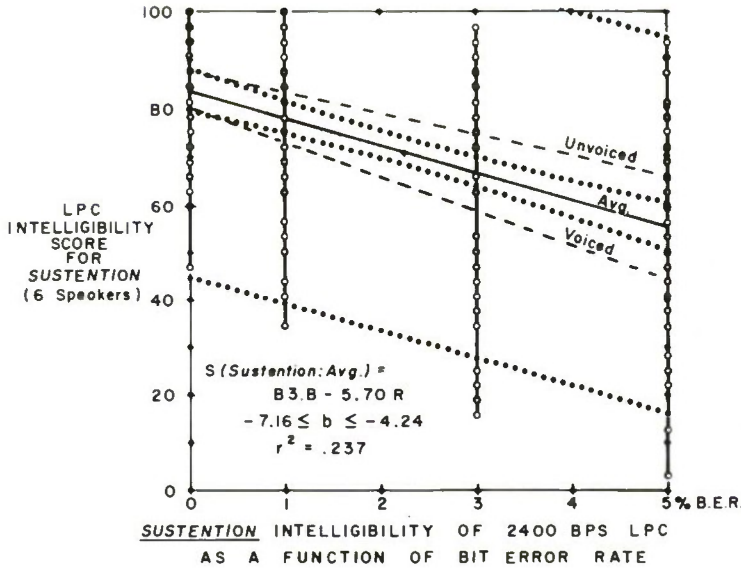
C.3.3. Analysis of Variance Summary: Sustention (Unvoiced).



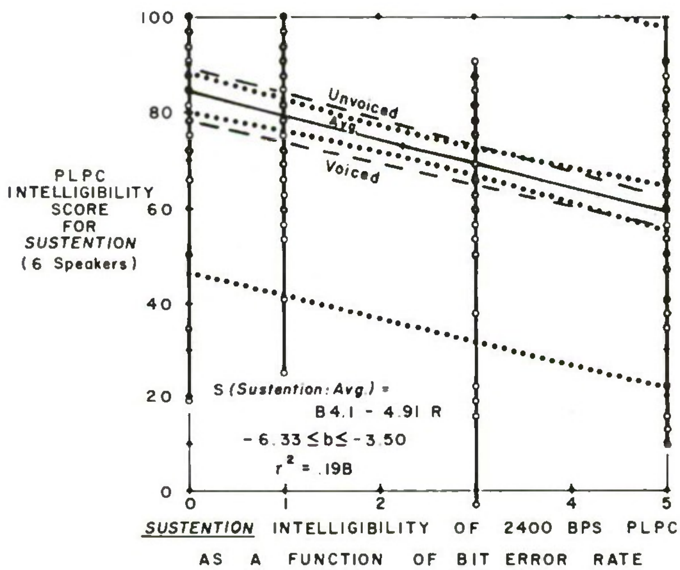
C.4.1. Cumulative distributions of the intelligibility scores for the Sustention feature, LPC-10 at 2400 BPS.



C.4.2. Cumulative distributions of the intelligibility scores for the Sustention feature, PLPC at 2400 BPS.



C.5.1. Scatter plot of scores, and linear regression model for the Sustention intelligibility feature, obtained with LPC-10 at 2400 BPS. Regression lines for the Voiced and Unvoiced conditions are also shown.



C.5.2. Scatter plot of scores, and linear regression model for the Sustention Intelligibility feature, obtained with PLPC at 2400 BPS. Regression lines for the Voiced and Unvoiced conditions are also shown.

Intelligibility of Sustention vs. Bit Error Rate, for 2400 BPS LPC-10

Model: S(LPC) = 83.75 - 5.700(BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of Sustention		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	83.8		79.43 ↔ 88.08	44.58 ↔ 122.93
1	78.1		74.70 ↔ 81.41	38.98 ↔ 117.13
2	72.4		69.52 ↔ 75.19	33.32 ↔ 111.39
3	66.7		63.64 ↔ 69.67	27.60 ↔ 105.70
4	61.0		57.15 ↔ 64.75	21.83 ↔ 100.07
5	55.3		50.34 ↔ 60.16	16.01 ↔ 94.49
6	50.0	↓	43.39 ↔ 55.72	10.13 ↔ 88.97
7	43.9	Extrapolated	36.35 ↔ 51.35	4.20 ↔ 83.50
8	38.2	Values	29.28 ↔ 47.02	- 1.78 ↔ 78.08
9	32.5		22.18 ↔ 42.72	- 7.81 ↔ 72.71
10%	26.7		15.07 ↔ 38.43	-13.90 ↔ 67.40

C.6.1. Predicted intelligibility scores for Sustention, LPC-10 at 2400 BPS with bit errors (with no provisions for error protection).

Intelligibility of Sustention vs. Bit Error Rate, for 2400 BPS PLPC

Model: S(PLPC) = 84.08 - 4.912(BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of Sustention		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	84.1		80.00 ↔ 88.26	46.23 ↔ 121.93
1	79.2		75.93 ↔ 82.41	41.41 ↔ 116.93
2	74.3		71.52 ↔ 76.99	36.54 ↔ 111.97
3	69.3		66.43 ↔ 72.26	31.61 ↔ 107.08
4	64.4		60.76 ↔ 68.11	26.63 ↔ 102.23
5	59.5		54.78 ↔ 64.26	21.60 ↔ 97.44
6	54.6	↓	48.65 ↔ 60.57	16.52 ↔ 92.70
7	49.7	Extrapolated	42.45 ↔ 56.94	11.39 ↔ 88.01
8	44.8	Values	36.22 ↔ 53.36	6.20 ↔ 83.37
9	39.9		29.95 ↔ 49.80	0.97 ↔ 78.78
10%	35.0		23.68 ↔ 46.25	- 4.31 ↔ 74.24

C.6.2. Predicted intelligibility scores for Sustention, PLPC at 2400 BPS with bit errors (with no provisions for error protection).

INTELLIGIBILITY FEATURE: *SIBILATION*

Test Items for *SIBILATION (Voiced)*

Sibilation Feature - Present		Sibilation Feature - Absent
ZEE	—	THEE
JILT	—	GILT
JEST	—	GUEST
JAB	—	GAB
JOT	—	GOT
JAWS	—	GAUZE
JOE	—	GO
JUICE	—	GOOSE

Test Items for *SIBILATION (Unvoiced)*

Sibilation Feature - Present		Sibilation Feature - Absent
CHEEP	—	KEEP
SING	—	THING
SANK	—	THANK
CHAIR	—	CARE
CHOP	—	COP
SAW	—	THAW
SOLE	—	THOLE
CHOO	—	COO

D.I. DRT test words for Sibilation.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Scores for SIBILATION feature.

Nr. of rows ("A" 's): [Processor Modes: LPC and PLPC at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"): [Scores for four SIBILATION states, x 2 presentations] 8= M

Values by rows:

	SIBILATION PRESENT		SIBILATION ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
LPC-10 at 2400 BPS.				
Zero bit error rate. Test #2050.				
Speaker LL	84.37	75.00	96.87	81.25
	78.12	65.62	100.00	87.50
Speaker RH	31.25	53.12	84.37	93.75
	46.87	68.75	96.87	93.75
Speaker CH	93.75	100.00	90.62	87.50
	90.62	96.87	96.87	96.87
Speaker PK	96.87	90.62	87.50	87.50
	96.87	90.62	96.87	96.87
Speaker JE	96.87	96.87	100.00	100.00
	96.87	100.00	100.00	100.00
Speaker BV	78.12	84.37	100.00	96.87
	81.25	87.50	100.00	100.00
1% bit error rate. Test #2051.				
Speaker LL	90.62	68.75	96.87	87.50
	93.75	65.62	93.75	81.25
Speaker RH	65.62	56.25	96.87	90.62
	46.87	90.62	84.37	93.75
Speaker CH	84.37	93.75	93.75	96.87
	84.37	100.00	93.75	93.75
Speaker PK	78.12	65.62	90.62	87.50
	93.75	78.12	90.62	100.00
Speaker JE	93.75	87.50	100.00	100.00
	90.62	93.75	100.00	100.00
Speaker BV	59.37	53.12	96.87	96.87
	75.00	46.87	100.00	96.87

D.2. Data Table: Sibilation Intelligibility Scores for LPC and PLPC.

LPC-10 at 2400 BPS - continued.

	SIBILATION PRESENT		SIBILATION ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
3% bit error rate. Test #2052.				
Speaker LL	78.12	56.25	84.37	87.50
	81.25	62.50	78.12	68.75
Speaker RH	78.12	68.75	90.62	90.62
	71.87	78.12	87.50	84.37
Speaker CH	78.12	84.37	84.37	100.00
	81.25	81.25	78.12	90.62
Speaker PK	78.12	78.12	68.75	90.62
	78.12	75.00	78.12	84.37
Speaker JE	71.87	68.75	96.87	87.50
	87.50	71.87	93.75	93.75
Speaker BV	65.62	78.12	90.62	93.75
	56.25	65.62	93.75	90.62
5% bit error rate. Test #2053.				
Speaker LL	90.62	62.50	87.50	68.75
	81.25	62.50	84.37	81.25
Speaker RH	28.12	46.87	90.62	87.50
	18.75	21.87	93.75	93.75
Speaker CH	71.87	81.25	81.25	93.75
	65.62	75.00	90.62	90.62
Speaker PK	71.87	53.12	78.12	87.50
	59.37	53.12	96.87	93.75
Speaker JE	84.37	56.25	75.00	96.87
	75.00	65.62	84.37	96.87
Speaker BV	84.37	84.37	87.50	93.75
	90.62	68.75	93.75	87.50

PLPC at 2400 BPS.

Zero bit error rate. Test #2043.

	Voiced	Unvoiced	Voiced	Unvoiced
Speaker LL	87.50	96.87	78.12	100.00
	93.75	96.87	78.12	93.75
Speaker RH	96.87	96.87	96.87	100.00
	96.87	100.00	90.62	90.62
Speaker CH	90.62	96.87	96.87	100.00
	93.75	100.00	96.87	100.00
Speaker PK	96.87	93.75	100.00	100.00
	93.75	100.00	93.75	93.75
Speaker JE	100.00	90.62	93.75	100.00
	100.00	96.87	96.87	93.75
Speaker BV	96.87	96.87	100.00	100.00
	100.00	100.00	100.00	100.00

D.2.-continued (part 2).

	SIBILATION PRESENT		SIBILATION ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
PLPC at 2400 BPS - cobninued.				
1% bit error rate. Test #2047.				
Speaker LL	96.87	75.00	90.62	93.75
	93.75	100.00	93.75	96.87
Speaker RH	81.25	78.12	100.00	96.87
	84.37	81.25	93.75	93.75
Speaker CH	93.75	65.62	81.25	100.00
	96.87	81.25	81.25	100.00
Speaker PK	90.62	84.37	84.37	100.00
	96.87	93.75	100.00	100.00
Speaker JE	96.87	84.37	87.50	100.00
	96.87	81.25	90.62	93.75
Speaker BV	78.12	93.75	96.87	100.00
	81.25	90.62	96.87	100.00
3% bit error rate. Test #2048.				
Speaker LL	90.62	75.00	81.25	96.87
	93.75	75.00	87.50	93.75
Speaker RH	81.25	68.75	96.87	93.75
	81.25	84.37	96.87	81.25
Speaker CH	96.87	81.25	96.87	100.00
	90.62	87.50	81.25	93.75
Speaker PK	93.75	65.62	81.25	90.62
	93.75	68.75	84.37	90.62
Speaker JE	96.87	78.12	81.25	100.00
	93.75	90.62	75.00	90.62
Speaker BV	84.37	71.87	90.62	96.87
	75.00	78.12	96.87	100.00
5% bit error rate. Test #2049.				
Speaker LL	87.50	75.00	78.12	90.62
	84.37	78.12	62.50	87.50
Speaker RH	71.87	50.00	84.37	78.12
	71.87	62.50	90.62	87.50
Speaker CH	87.50	84.37	90.62	75.00
	87.50	81.25	84.37	71.87
Speaker PK	93.75	34.37	84.37	84.37
	93.75	34.37	59.37	87.50
Speaker JE	75.00	68.75	87.50	96.87
	78.12	65.62	87.50	93.75
Speaker BV	46.87	65.62	90.62	100.00
	75.00	65.62	81.25	100.00

D.2.-continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC at 2400 BPS with bit errors:
Intelligibility Scores for SIBILATION.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio
Replications	7	15138.37697	2162.62528	
"A" 's (processors)	1	2604.53128	2604.53128	24.18707*** (p=.9999)
"B" 's (speakers)	5	4347.96147	869.59229	8.07550*** (p=.9999)
"C" 's (BER's)	3	11972.38428	3990.79476	37.06066*** (p=.9999)
AB Interactions	5	1927.09282	385.41856	3.57920** (p=.9963)
AC Interactions	3	437.32520	145.77506	1.35374 (p=.7184)
BC Interactions	15	2671.46153	178.09743	1.65390 (p=.9340)
ABC Interactions	15	2430.12701	162.00846	1.50449 (p=.8814)
Error	329	35427.62907	107.68276	
Total	383	76956.88963		

D.3.1. Analysis of Variance Summary: Sibilation (Total).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC at 2400 BPS with bit errors:

Intelligibility Scores for SIBILATION(Voiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	2489.78529	829.92843		
"A" 's (processors)	1	1286.14283	1286.14283	10.70743 **	(p=.9987)
"B" 's (speakers)	5	2256.01137	451.20227	3.75636 **	(p=.9968)
"C" 's (BER's)	3	4264.13746	1421.37915	11.83331 ***	(p=.9999)
AB Interactions	5	2198.94949	439.78989	3.66135 **	(p=.9961)
AC Interactions	3	190.22861	63.40953	.52789	
BC Interactions	15	1763.07891	117.53859	.97853	
ABC Interactions	15	1933.97803	128.93186	1.07338	(p=.3197)
Error	141	16936.46174	120.11674		
Total	191	33318.77373			

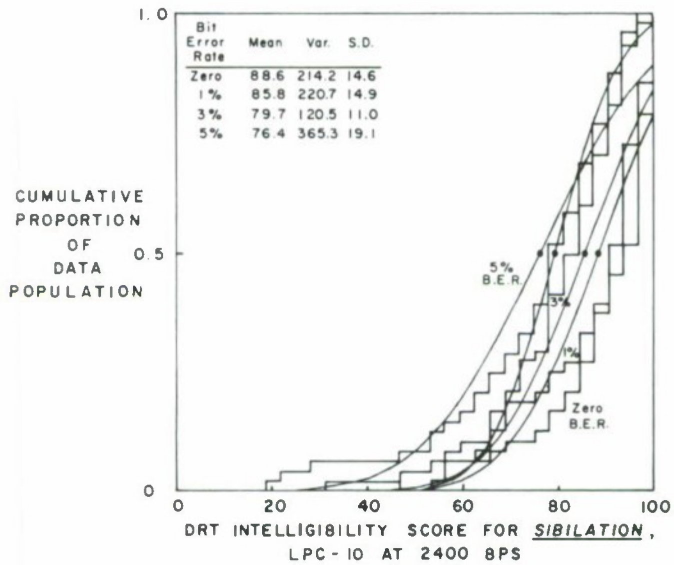
D.3.2. Analysis of Variance Summary: Sibilation (Voiced).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

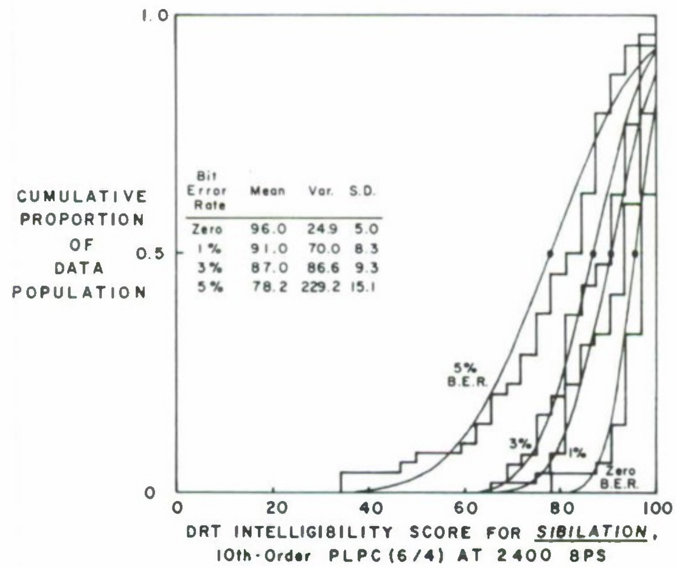
Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Intelligibility Scores for SIBILATION(Unvoiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	12501.88588	4167.29529		
"A" 's (processors)	1	1318.48885	1318.48885	14.52883***	(p=.9998)
"B" 's (speakers)	5	3005.84893	601.16978	6.62447***	(p=.9999)
"C" 's (BER's)	3	8053.93792	2684.64597	29.58294***	(p=.9999)
AB Interactions	5	2002.59175	400.51835	4.41343***	(p=.9991)
AC Interactions	3	411.65211	137.21737	1.51204	(p=.7699)
BC Interactions	15	1651.59292	110.10619	1.21329	(p=.6243)
ABC Interactions	15	1749.69127	116.64608	1.28535	(p=.7134)
Error	141	12795.72047	90.74979		
Total	191	43491.41010			

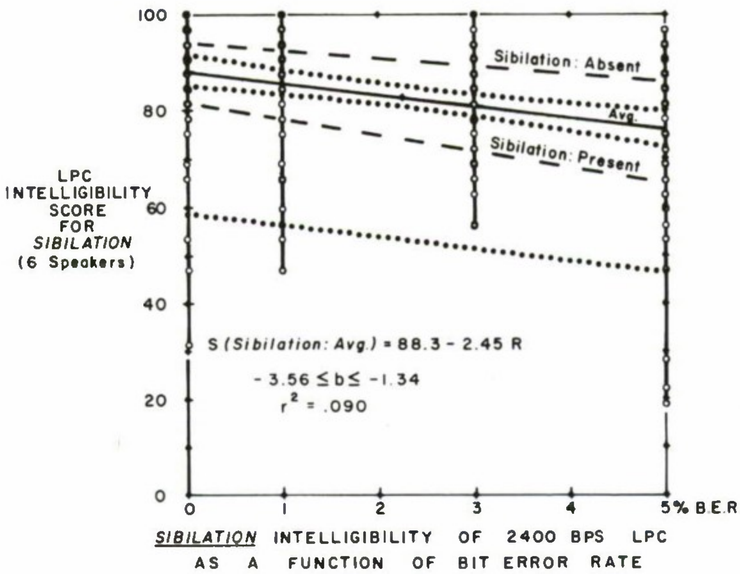
D.3.3. Analysis of Variance Summary: Sibilation (Unvoiced).



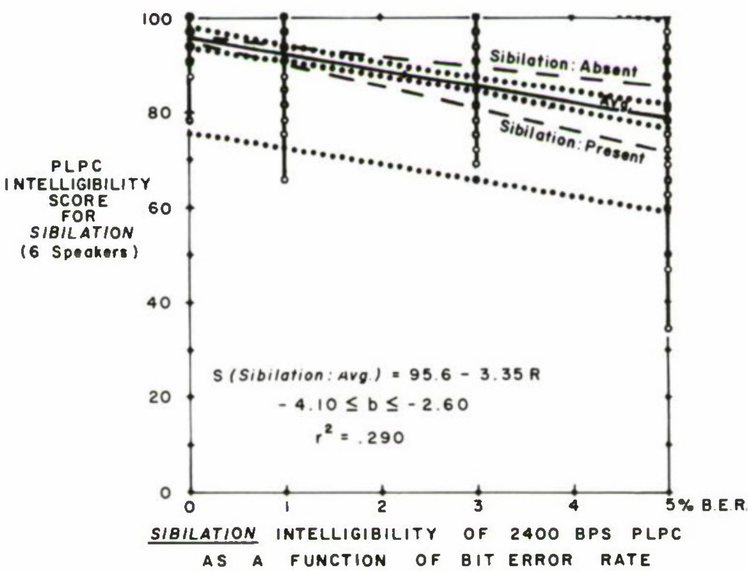
D.4.1. Cumulative distributions of the intelligibility scores for the Sibilation feature, LPC-10 at 2400 BPS.



D.4.2. Cumulative Distributions of the intelligibility scores for the Sibilation feature, PLPC at 2400 BPS.



D.5.1. Scatter plot of scores, and linear regression model for the Sibilation intelligibility feature, obtained with LPC-10 at 2400 BPS. Regression lines for Sibilation-Present and Sibilation-Absent are also shown.



D.5.2. Scatter plot of scores, and linear regression model for the Sibilation Intelligibility feature, obtained with PLPC at 2400 BPS. Regression lines for Sibilation-Present and Sibilation-Absent are also shown.

Intelligibility of Sibilation vs. Bit Error Rate, for 2400 BPS LPC-10

Model: S(LPC) = 88.33 - 2.446(BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of Sibilation		95% Confidence Limits	
			Expected Avg. Score	Individual Scores
0	88.3		85.04↔91.62	58.58↔118.08
1	85.9		83.34↔88.43	56.21↔115.56
2	83.4		81.29↔85.59	53.80↔113.08
3	81.0		78.70↔83.28	51.34↔110.64
4	78.5		75.66↔81.43	48.84↔108.25
5	76.1		72.37↔79.83	46.30↔105.90
6	73.7	↓	68.97↔78.33	43.72↔103.59
7	71.2	Extrapolated	65.51↔76.90	41.10↔101.31
8	68.8	Values	62.02↔75.50	38.44↔99.08
9	66.3		58.52↔74.11	35.74↔96.89
10%	63.9		55.00↔72.74	33.00↔94.73

D.6.1. Predicted intelligibility scores for Sibilation, LPC-10 at 2400 BPS with bit errors (with no provisions for error protection).

Intelligibility of Sibilation vs. Bit Error Rate, for 2400 BPS PLPC

Model: S(PLPC) = 95.58 - 3.351 (BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of Sibilation		95% Confidence Limits	
			Expected Avg. Score	Individual Scores
0	95.6		93.35 - 97.80	75.48 - 115.67
1	92.2		90.50 - 93.94	72.17 - 112.27
2	88.9		87.42 - 90.33	68.84 - 108.90
3	85.5		83.97 - 87.07	65.49 - 105.56
4	82.2		80.22 - 84.12	62.10 - 102.24
5	78.8		76.30 - 81.34	58.68 - 98.95
6	75.5	↓	72.30 - 78.63	55.24 - 95.69
7	72.1	Extrapolated	68.27 - 75.96	51.77 - 92.46
8	68.8	Values	64.21 - 73.32	48.28 - 89.25
9	65.4		60.14 - 70.68	44.75 - 86.07
10%	62.1		56.07 - 68.06	41.21 - 82.92

D.6.2. Predicted intelligibility scores for Sibilation, PLPC at 2400 BPS with bit errors (with no provisions for error protection).

INTELLIGIBILITY FEATURE: *GRAVENESS*

Test Items for *GRAVENESS (Voiced)*

Graveness Feature - Present		Graveness Feature - Absent
WEED	—	REED
BID	—	DID
MET	—	NET
BANK	—	DANK
WAD	—	ROD
BONG	—	DONG
BOWL	—	DOLE
MOON	—	NOON

Test Items for *GRAVENESS (Unvoiced)*

Graveness Feature - Present		Graveness Feature - Absent
PEEK	—	TEAK
FIN	—	THIN
PENT	—	TENT
FAD	—	THAD
POT	—	TOT
FOUGHT	—	THOUGHT
FORE	—	THOR
POOL	—	TOOL

E.1. DRT test words for Graveness.

INTELLIGIBILITY FEATURE: *GRAVENESS (II.)*

Test items for *GRAVENESS (Stopped)*

Graveness Feature: Present		Graveness Feature: Absent
PEEK	—	TEAK
BID	—	DID
PENT	—	TENT
BANK	—	DANK
POT	—	TOT
BONG	—	DONG
BOWL	—	DOLE
POOL	—	TOOL

Test items for *GRAVENESS (Unstopped)*

Graveness Feature: Present		Graveness Feature: Absent
WEED	—	REED
FIN	—	THIN
MET	—	NET
FAD	—	THAD
WAD	—	ROD
FOUGHT	—	THOUGHT
FORE	—	THOR
MOON	—	NOON

E.I. (part 2) DRT test words for Graveness grouped to permit scoring Graveness(Stopped) vs. Graveness(Unstopped). (This scoring option was not utilized in this battery of tests).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Scores for GRAVENESS.

Nr. of rows ("A" 's): [Processor Modes: LPC and PLPC at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"):[Four states of GRAVENESS x 2 presentations] 8= M

Values by rows:	GRAVENESS PRESENT		GRAVENESS ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
LPC at 2400 BPS.				
Zero bit error rate. Test #2050.				
Speaker LL	87.50	59.37	93.75	75.00
	87.50	81.25	93.75	71.87
Speaker RH	93.75	71.87	100.00	50.00
	96.87	75.00	96.87	40.62
Speaker CH	96.87	84.37	93.75	65.62
	96.87	75.00	87.50	68.75
Speaker PK	93.75	71.87	96.87	71.87
	90.62	81.25	100.00	75.00
Speaker JE	100.00	56.25	100.00	87.50
	93.75	65.62	96.87	100.00
Speaker BV	90.62	90.62	100.00	46.87
	100.00	84.37	100.00	59.37
1% bit error rate. Test #2051.				
Speaker LL	84.37	65.62	100.00	65.62
	75.00	78.12	96.87	68.75
Speaker RH	87.50	62.50	96.87	50.00
	93.75	65.62	100.00	40.62
Speaker CH	78.12	68.75	87.50	62.50
	81.25	78.12	93.75	75.00
Speaker PK	56.25	50.00	93.75	59.37
	65.62	65.62	96.87	53.12
Speaker JE	87.50	59.37	84.37	87.50
	78.12	53.12	87.50	90.62
Speaker BV	100.00	81.25	96.87	53.12
	100.00	84.37	100.00	40.62

E.2. Data Table: Graveness Intelligibility Scores for LPC and PLPC.

	GRAVENESS PRESENT		GRAVENESS ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
(LPC at 2400 BPS).				
3% bit error rate. Test #2052.				
Speaker LL	93.75	37.50	53.12	53.12
	96.87	37.50	56.25	56.25
Speaker RH	84.37	53.12	84.37	12.50
	96.87	37.50	78.12	15.62
Speaker CH	78.12	40.62	93.75	62.50
	84.37	53.12	93.75	71.87
Speaker PK	46.87	46.87	71.87	53.12
	65.62	62.50	78.12	53.12
Speaker JE	78.12	40.62	90.62	46.87
	75.00	40.62	96.87	40.62
Speaker BV	75.00	62.50	93.75	28.12
	78.12	68.75	90.62	40.62
5% bit error rate. Test #2053.				
Speaker LL	59.37	62.50	75.00	12.50
	65.62	56.25	84.37	9.37
Speaker RH	40.62	50.00	78.12	21.87
	40.62	37.50	75.00	-3.12
Speaker CH	81.25	65.62	65.62	6.25
	71.87	59.37	59.37	18.75
Speaker PK	56.25	37.50	87.50	31.25
	53.12	50.00	90.62	37.50
Speaker JE	59.37	37.50	78.12	40.62
	62.50	3.12	87.50	46.87
Speaker BV	65.62	56.25	65.62	25.00
	65.62	40.62	62.50	31.25
PLPC at 2400 BPS.				
Zero bit error rate. Test #2043.				
Speaker LL	100.00	71.87	84.37	84.37
	100.00	68.75	87.50	81.25
Speaker RH	96.87	62.50	93.75	53.12
	100.00	56.25	100.00	78.12
Speaker CH	100.00	81.25	100.00	90.62
	100.00	78.12	100.00	93.75
Speaker PK	93.75	84.37	96.87	78.12
	93.75	75.00	96.87	78.12
Speaker JE	96.87	53.12	100.00	84.37
	100.00	62.50	93.75	87.50
Speaker BV	100.00	84.37	100.00	78.12
	100.00	87.50	100.00	78.12

E.2.-continued (part 2).

	GRAVENESS PRESENT		GRAVENESS ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
(PLPC at 2400 BPS)				
1% bit error rate. Test #2047.				
Speaker LL	81.25	75.00	68.75	65.62
	75.00	65.62	81.25	65.62
Speaker RH	96.87	87.50	90.62	62.50
	96.87	65.62	87.50	65.62
Speaker CH	96.87	71.87	93.75	87.50
	100.00	68.75	96.87	87.50
Speaker PK	71.87	65.62	100.00	37.50
	68.75	40.62	100.00	56.25
Speaker JE	90.62	56.25	90.62	68.75
	93.75	46.87	96.87	84.37
Speaker BV	87.50	96.87	93.75	34.37
	84.37	78.12	100.00	50.00
3% bit error rate. Test #2048.				
Speaker LL	90.62	43.75	78.12	56.25
	87.50	62.50	87.50	62.50
Speaker RH	90.62	46.87	96.87	21.87
	96.87	34.37	100.00	28.12
Speaker CH	46.87	56.25	96.87	71.87
	43.75	28.12	96.87	75.00
Speaker PK	87.50	68.75	100.00	37.50
	87.50	62.50	93.75	50.00
Speaker JE	87.50	9.37	93.75	59.37
	84.37	9.37	96.87	81.25
Speaker BV	81.25	53.12	100.00	25.00
	90.62	68.75	100.00	43.75
5% bit error rate. Test #2049.				
Speaker LL	56.25	-6.25	75.00	34.37
	62.50	-9.37	78.12	50.00
Speaker RH	68.75	59.37	78.12	12.50
	53.12	56.25	78.12	6.25
Speaker CH	53.12	46.87	96.87	53.12
	43.75	34.37	93.75	65.62
Speaker PK	56.25	40.62	84.37	34.37
	59.37	34.37	90.62	46.87
Speaker JE	43.75	62.50	56.25	81.25
	71.87	50.00	71.87	78.12
Speaker BV	56.25	87.50	78.12	18.75
	75.00	84.37	93.75	34.37

E.2.-continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Intelligibility Scores for GRAVENESS.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	7	81384.74403	11626.39200		
"A" 's (processors)	1	1287.69837	1287.69837	5.88737 *	(p=.9847)
"B" 's (speakers)	5	3292.34438	658.46887	3.01052 *	(p=.9883)
"C" 's (BER's)	3	52328.03163	17442.67721	79.74814 ***	(p=.9999)
AB Interactions	5	495.40886	99.08177	.45300	
AC Interactions	3	279.84936	93.28312	.42649	
BC Interactions	15	2731.82522	182.12168	.83266	
ABC Interactions	15	3546.02701	236.40180	1.08083	(p=.3430)
Error	329	71959.54911	218.72203		
Total	383	217305.47797			

E.3.1. Analysis of Variance Summary: Graveness (Total).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:

Intelligibility Scores for <u>GRAVENESS(Voiced)</u>.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	4035.95996	1345.31998		
"A" 's (processors)	1	449.60581	449.60581	4.26878*	(p=.9611)
"B" 's (speakers)	5	1153.94146	230.78829	2.19122	(p=.9381)
"C" 's (BER's)	3	19298.40145	6432.80048	61.07624***	(p=.9999)
AB Interactions	5	461.88738	92.37747	.87707	
AC Interactions	3	330.71128	110.23709	1.04664	(p=.5680)
BC Interactions	15	1902.95901	126.86393	1.20451	(p=.6114)
ABC Interactions	15	3172.56912	211.50460	2.00813*	(p=.9803)
Error	141	14850.69717	105.32409		
Total	191	45656.73264			

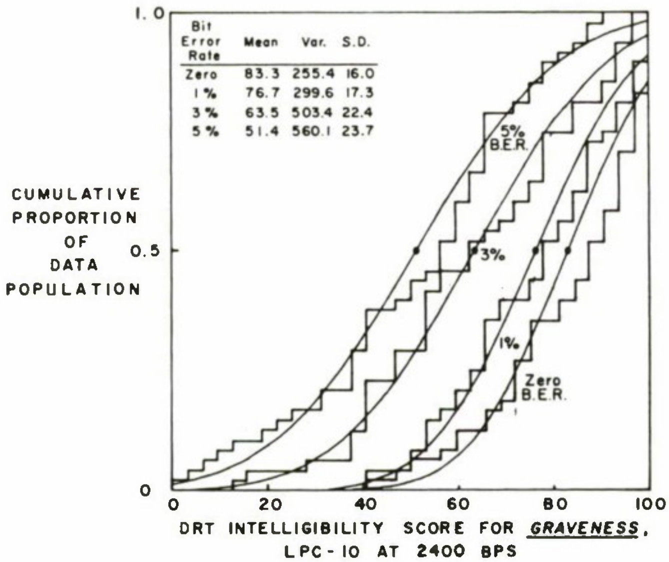
E.3.2. Analysis of Variance Summary: <u>Graveness (Voiced)</u>.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

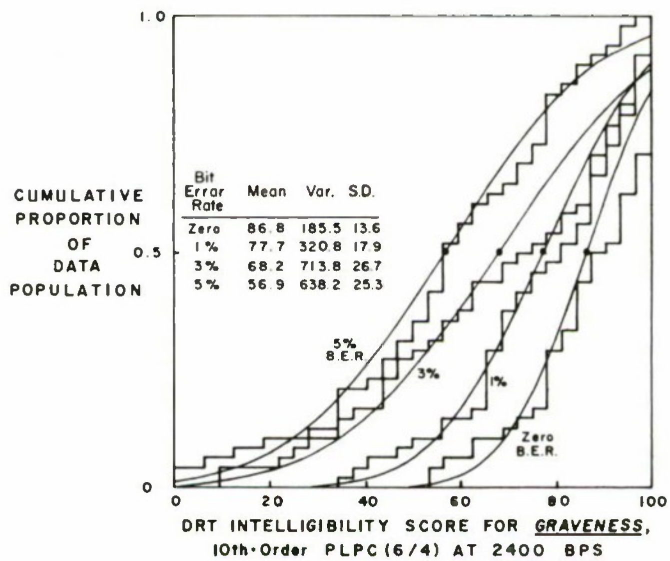
Reference: Comparison of LPC and PLPC Intelligibility at 2400 BPS with bit errors:
Intelligibility Scores for GRAVENESS(Unvoiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	1497.60327	499.20109		
"A" 's (processors)	1	872.87492	872.87492	3.02489	(p=.9217)
"B" 's (speakers)	5	5631.79910	1126.35982	3.90333**	(p=.9976)
"C" 's (BER's)	3	36277.40082	12092.46694	41.90571***	(p=.9999)
AB Interactions	5	687.43711	137.48742	.47645	
AC Interactions	3	509.36762	169.78920	.58839	
BC Interactions	15	5564.3[illegible]595	370.95639	1.28552	(p=.7136)
ABC Interactions	15	4069.25604	271.28373	.94011	
Error	141	40687.47967	288.56368		
Total	191	95797.56453			

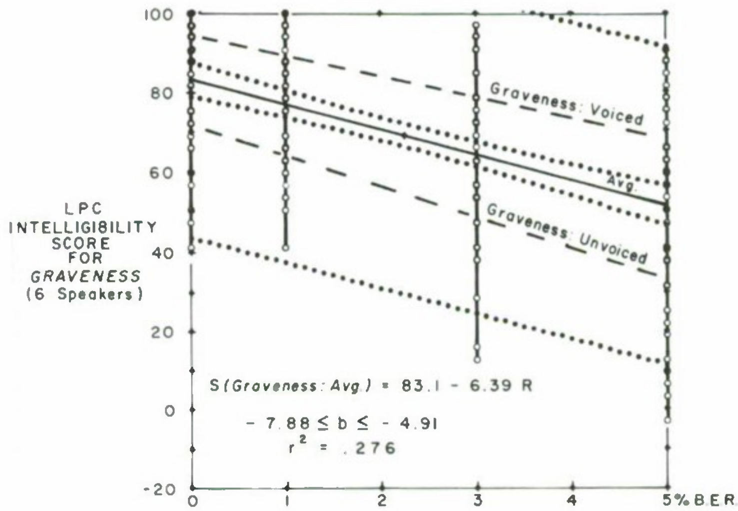
E.3.3. Analysis of Variance Summary: Graveness (Unvoiced).



E.4.1. Cumulative distributions of the intelligibility scores for the Graveness feature, LPC-10 at 2400 BPS.



E.4.2. Cumulative distributions of the intelligibility scores for the Graveness feature, PLPC at 2400 BPS.



<u>GRAVENESS</u> INTELLIGIBILITY OF 2400 BPS LPC
AS A FUNCTION OF BIT ERROR RATE

E.5.1. Scatter plot of scores, and linear regression model for the <u>Graveness</u> intelligibility feature, obtained with LPC-10 at 2400 BPS. Regression lines for the <u>Voiced</u> and <u>Unvoiced</u> conditions are also shown.

Intelligibility of <u>*Graveness*</u> <u>*vs*</u> <u>Bit Error Rate</u>, for 2400 BPS PLPC

Model: S(PLPC) = 85.31 − 5.746 (BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of *Graveness*		95% Confidence Limits: *Expected Avg. Score*	95% Confidence Limits: *Individual Scores*
0	85.3		80.60 ↔ 90.01	42.68 ↔ 127.93
1	79.6		75.91 ↔ 83.21	37.04 ↔ 122.08
2	73.8		70.73 ↔ 76.90	31.34 ↔ 116.29
3	68.1		64.79 ↔ 71.35	25.58 ↔ 110.56
4	62.3		58.19 ↔ 66.46	19.76 ↔ 104.89
5	56.6		51.24 ↔ 61.92	13.88 ↔ 99.27
6	50.8	↓	44.12 ↔ 57.54	7.94 ↔ 93.72
7	45.1	*Extrapolated*	36.93 ↔ 53.24	1.94 ↔ 88.22
8	39.3	*Values*	29.69 ↔ 48.99	-4.11 ↔ 82.79
9	33.6		22.42 ↔ 44.77	-10.22 ↔ 77.40
10%	27.8		15.14 ↔ 40.56	-16.38 ↔ 72.07

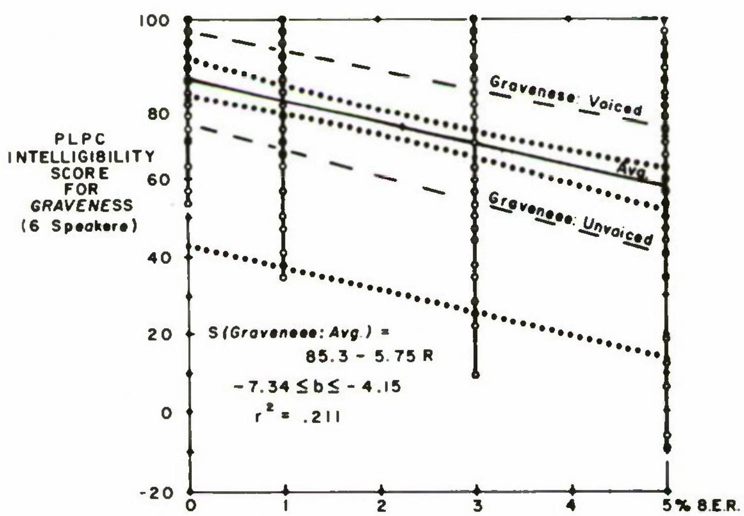
E.6.2. Predicted intelligibility scores for <u>Graveness</u>, PLPC at 2400 BPS with bit errors (with no provisions for error protection).

Intelligibility of Graveness' vs. Bit Error Rate, for 2400 BPS LPC-10

Model: S(LPC) = 83.10 - 6.394(BER%) (Based on 192 points)

Bit Error Rate	Intelligibility of Graveness		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	83.1		78.72↔87.49	43.39↔122.82
1	76.7		73.31↔80.12	37.09↔116.33
2	70.3		67.44↔73.19	30.74↔109.89
3	63.9		60.86↔66.98	24.33↔103.51
4	57.5		53.67↔61.38	17.87↔97.19
5	51.1		46.16↔56.11	11.35↔90.92
6	44.7	↓	38.49↔50.99	4.77↔84.70
7	38.3	Extrapolated	30.74↔45.94	-1.85↔78.54
8	31.9	Values	22.96↔40.94	-8.54↔72.43
9	25.6		15.14↔35.97	-15.27↔66.38
10%	19.2		7.32↔31.00	-22.05↔60.37

E.6.1. Predicted intelligibility scores for Graveness, LPC-10 at 2400 BPS with bit errors (with no provisions for error protection).



E.5.2. Scatter plot of scores, and linear regression model for the Graveness Intelligibility feature, obtained with PLPC at 2400 BPS. Regression lines for the Voiced and Unvoiced conditions are also shown.

INTELLIGIBILITY FEATURE: *COMPACTNESS*

Test Items for *COMPACTNESS (Voiced)*

Compactness Feature - Present		Compactness Feature - Absent
YIELD	—	WIELD
GILL	—	DILL
YEN	—	WREN
GAT	—	BAT
GOT	—	DOT
YAWL	—	WALL
GHOST	—	BOAST
YOU	—	RUE

Test Items for *COMPACTNESS (Unvoiced)*

Compactness Feature - Present		Compactness Feature - Absent
KEY	—	TEA
HIT	—	FIT
KEG	—	PEG
SHAG	—	SAG
HOP	—	FOP
CAUGHT	—	TAUGHT
SHOW	—	SO
COOP	—	POOP

F.I. DRT test words for Compactness.

INTELLIGIBILITY FEATURE. *COMPACTNESS (II.)*

Test items for *COMPACTNESS (Sustained)*

Compactness Feature : Present		Compactness Feature : Absent
YIELD	—	WIELD
HIT	—	FIT
YEN	—	WREN
SHAG	—	SAG
HOP	—	FOP
YAWL	—	WALL
SHOW	—	SO
YOU	—	RUE

Test items for *COMPACTNESS (Interrupted)*

Compactness Feature : Present		Compactness Feature : Absent
KEY	—	TEA
GILL	—	DILL
KEG	—	PEG
GAT	—	BAT
GOT	—	DOT
CAUGHT	—	TAUGHT
GHOST	—	BOAST
COOP	—	POOP

F.I. (part 2) DRT test words for Compactness grouped to permit scoring Compactness(Sustained) vs. Compactness(Interrupted). (This scoring option was not utilized in this battery of tests).

INTELLIGIBILITY FEATURE: *COMPACTNESS (III.)*

Test items for *COMPACTNESS (Back vs. Middle)*

Compactness Feature : Present		Compactness Feature : Absent
YIELD	—	WIELD
HIT	—	FIT
KEG	—	PEG
GAT	—	BAT
HOP	—	FOP
YAWL	—	WALL
GHOST	—	BOAST
COOP	—	POOP

Test items for *COMPACTNESS (Back vs. Front)*

Compactness Feature : Present		Compactness Feature : Absent
KEY	—	TEA
GILL	—	DILL
YEN	—	WREN
SHAG	—	SAG
GOT	—	DOT
CAUGHT	—	TAUGHT
SHOW	—	SO
YOU	—	RUE

F.I. (part 3) DRT test words for Compactness grouped to permit scoring Compactness(Back vs. Middle) vs. Compactness(Back vs. Front). (This scoring option was not utilized in this battery of tests).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Intelligibility Scores for <u>COMPACTNESS</u>.

Nr. of rows ("A" 's): [Processor Modes: LPC and PLPC, at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"): [Four COMPACTNESS states, x 2 presentations] 8= M

Values by rows: COMPACTNESS PRESENT / COMPACTNESS ABSENT

LPC at 2400 BPS.

Zero bit error rate. Test #2050.

	COMPACTNESS PRESENT Voiced	COMPACTNESS PRESENT Unvoiced	COMPACTNESS ABSENT Voiced	COMPACTNESS ABSENT Unvoiced
Speaker LL	96.87	100.00	100.00	81.25
	100.00	100.00	100.00	96.87
Speaker RH	100.00	84.37	100.00	93.75
	100.00	65.62	100.00	84.37
Speaker CH	100.00	100.00	96.87	87.50
	100.00	96.87	100.00	93.75
Speaker PK	90.62	93.75	96.87	84.37
	96.87	100.00	100.00	90.62
Speaker JE	100.00	100.00	100.00	87.50
	100.00	93.75	100.00	90.62
Speaker BV	100.00	96.87	100.00	100.00
	93.75	100.00	100.00	100.00

1% bit error rate. Test #2051.

	COMPACTNESS PRESENT Voiced	COMPACTNESS PRESENT Unvoiced	COMPACTNESS ABSENT Voiced	COMPACTNESS ABSENT Unvoiced
Speaker LL	100.00	100.00	93.75	75.00
	100.00	93.75	96.87	75.00
Speaker RH	100.00	78.12	100.00	75.00
	100.00	87.50	100.00	78.12
Speaker CH	100.00	100.00	100.00	90.62
	100.00	100.00	100.00	96.87
Speaker PK	87.50	90.62	84.37	43.75
	84.37	84.37	90.62	59.37
Speaker JE	100.00	93.75	100.00	75.00
	100.00	87.50	100.00	75.00
Speaker BV	100.00	93.75	93.75	100.00
	100.00	96.87	100.00	93.75

F.2. Data Table: <u>Compactness</u> Intelligibility Scores for LPC and PLPC.

	Compactness Present: Voiced	Compactness Present: Unvoiced	Compactness Absent: Voiced	Compactness Absent: Unvoiced
(LPC at 2400 BPS).				
3% bit error rate. Test #2052.				
Speaker LL	100.00	87.50	90.62	59.37
	100.00	81.25	90.62	56.25
Speaker RH	100.00	53.12	100.00	59.37
	93.75	59.37	93.75	50.00
Speaker CH	100.00	81.25	78.12	90.62
	100.00	84.37	78.12	87.50
Speaker PK	90.62	87.50	100.00	56.25
	93.75	93.75	100.00	59.37
Speaker JE	96.87	87.50	100.00	87.50
	100.00	84.37	100.00	75.00
Speaker BV	90.62	96.87	96.87	59.37
	90.62	93.75	93.75	62.50
5% bit error rate. Test #2053.				
Speaker LL	84.37	81.25	100.00	50.00
	84.37	78.12	87.50	56.25
Speaker RH	75.00	68.75	96.87	46.87
	75.00	62.50	100.00	37.50
Speaker CH	96.87	96.87	71.87	100.00
	100.00	90.62	78.12	96.87
Speaker PK	87.50	81.25	87.50	62.50
	84.37	59.37	87.50	75.00
Speaker JE	87.50	78.12	68.75	71.87
	84.37	62.50	68.75	56.25
Speaker BV	90.62	75.00	87.50	71.87
	90.62	68.75	84.37	65.62
PLPC at 2400 BPS.				
Zero bit error rate.				
Speaker LL	100.00	100.00	96.87	65.62
	96.87	96.87	96.87	68.75
Speaker RH	93.75	96.87	100.00	75.00
	96.87	100.00	100.00	78.12
Speaker CH	100.00	100.00	100.00	100.00
	100.00	100.00	100.00	96.87
Speaker PK	75.00	100.00	96.87	71.87
	81.25	100.00	100.00	81.25
Speaker JE	100.00	96.87	100.00	87.50
	100.00	96.87	100.00	81.25
Speaker BV	100.00	100.00	100.00	100.00
	100.00	100.00	100.00	100.00

F.2.-continued (part 2).

	COMPACTNESS PRESENT		COMPACTNESS ABSENT	
	Voiced	Unvoiced	Voiced	Unvoiced
(PLPC at 2400 BPS)				
1% bit error rate. Test #2047.				
Speaker LL	96.87	93.75	81.25	87.50
	100.00	100.00	84.37	87.50
Speaker RH	100.00	71.87	90.62	71.87
	93.75	71.87	96.87	71.87
Speaker CH	100.00	87.50	100.00	87.50
	100.00	100.00	100.00	75.00
Speaker PK	81.25	90.62	93.75	75.00
	84.37	96.87	100.00	68.75
Speaker JE	93.75	96.87	93.75	90.62
	93.75	87.50	93.75	96.87
Speaker BV	96.87	93.75	100.00	100.00
	96.87	93.75	100.00	93.75
3% bit error rate. Test #2048.				
Speaker LL	96.87	90.62	78.12	65.62
	100.00	100.00	90.62	62.50
Speaker RH	96.87	84.37	100.00	62.50
	96.87	71.87	100.00	78.12
Speaker CH	93.75	93.75	96.87	62.50
	96.87	100.00	96.87	68.75
Speaker PK	53.12	90.62	87.50	71.87
	62.50	90.62	93.75	93.75
Speaker JE	93.75	62.50	96.87	96.87
	93.75	84.37	100.00	93.75
Speaker BV	96.87	68.75	93.75	90.62
	93.75	81.25	93.75	84.37
5% bit error rate. Test #2049.				
Speaker LL	93.75	87.50	93.75	59.37
	100.00	96.87	96.87	59.37
Speaker RH	96.87	62.50	100.00	56.25
	93.75	53.12	100.00	65.62
Speaker CH	96.87	50.00	84.37	28.12
	93.75	56.25	87.50	34.37
Speaker PK	40.62	78.12	93.75	65.62
	40.62	65.62	96.87	65.62
Speaker JE	78.12	25.00	90.62	78.12
	84.37	43.75	100.00	87.50
Speaker BV	84.37	59.37	87.50	71.87
	75.00	65.62	78.12	68.75

F. 2. -continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:

Intelligibility Scores for COMPACTNESS.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	7	19894.25086	2842.03583		
"A" 's (processors)	1	82.68666	82.68666	.69922	
"B" 's (speakers)	5	3506.89566	701.37913	5.93111***	(p=.9999)
"C" 's (BER's)	3	18879.23222	6293.07740	53.21652***	(p=.9999)
AB Interactions	5	933.66621	186.73324	1.57908	(p=.8131)
AC Interactions	3	374.84963	124.94987	1.05662	(p=.5744)
BC Interactions	15	1982.73456	132.18230	1.11778	(p=.4498)
ABC Interactions	15	3603.38068	240.22537	2.03143*	(p=.9862)
Error	329	38905.62793	118.25418		
Total	383	88163.32441			

F.3.1. Analysis of Variance Summary: Compactness (Total).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Intelligibility Scores for COMPACTNESS(Voiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	194.14519	64.71506		
"A" 's(processors)	1	107.67025	107.67025	1.82946	(p=.8440)
"B" 's(speakers)	5	2395.78065	479.15613	8.14150***	(p=.9999)
"C" 's(BER's)	3	3693.52286	1231.17428	20.91929***	(p=.9999)
AB Interactions	5	1026.24190	205.24838	3.48744**	(p=.9946)
AC Interactions	3	128.80176	42.93392	.72950	
BC Interactions	15	888.97145	59.26476	1.00698	(p=.0165)
ABC Interactions	15	1647.59092	109.83939	1.86631*	(p=.9660)
Error	141	8298.34771	58.85352		
Total	191	18381.07269			

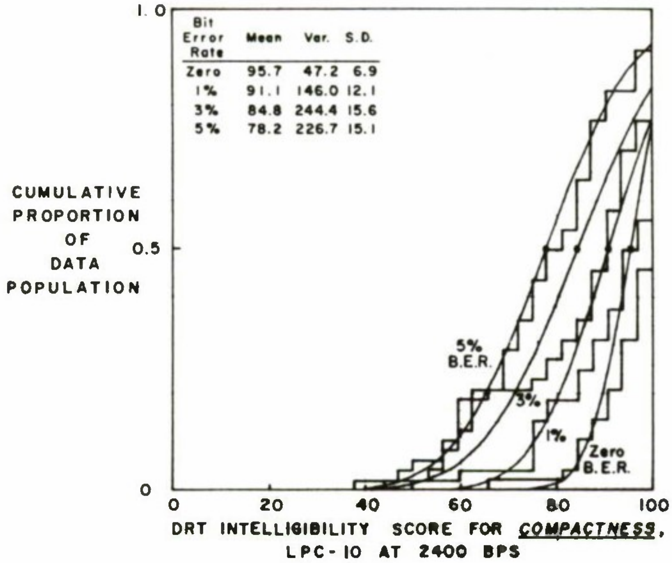
F.3.2. Analysis of Variance Summary: Compactness (Voiced).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

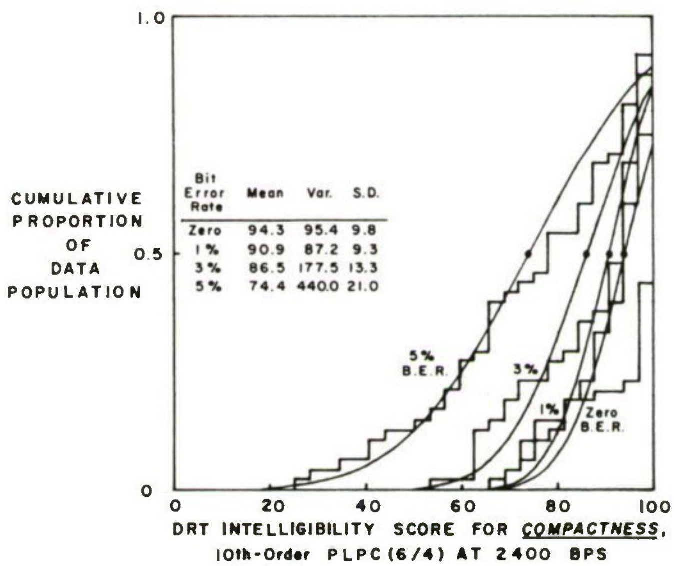
Reference: Comparison of LPC and PLPC Intelligibility Scores at 2400 BPS with bit errors:
Intelligibility Scores for COMPACTNESS(Unvoiced).

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	
Replications	3	3867.48642	1289.16214		
"A" 's (processors)	1	6.16692	6.16692	.05395	
"B" 's (speakers)	5	5014.06737	1002.81347	8.77405 ***	(p=.9999)
"C" 's (BER's)	3	17964.07824	5988.02608	52.39185 ***	(p=.9999)
AB Interactions	5	2535.65980	507.13196	4.43711 ***	(p=.9991)
AC Interactions	3	1478.14201	492.71400	4.31097 **	(p=.9939)
BC Interactions	15	2177.06592	145.13772	1.26987	(p=.6965)
ABC Interactions	15	4791.64276	319.44285	2.79494 ***	(p=.9992)
Error	141	16115.32301	114.29307		
Total	191	53949.63245			

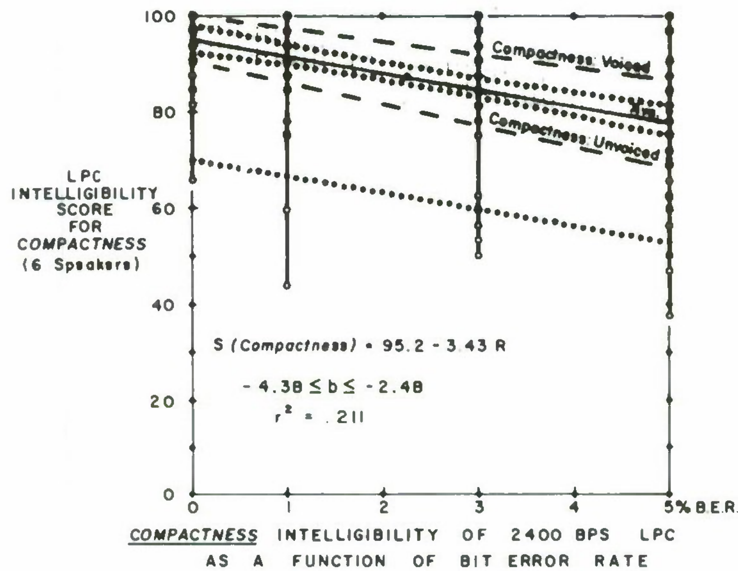
F.3.3. Analysis of Variance Summary: Compactness (Unvoiced).



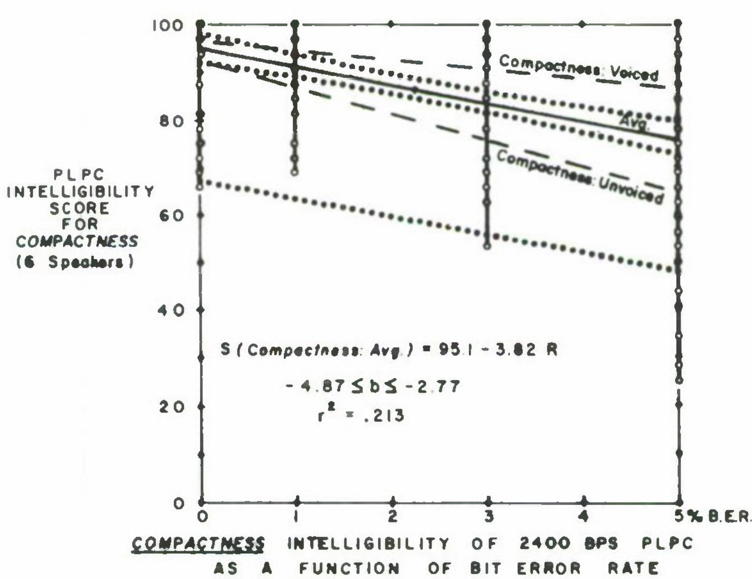
F.4.1. Cumulative distributions of the intelligibility scores for the Compactness feature, LPC-10 at 2400 BPS.



F.4.2. Cumulative distributions of the intelligibility scores for the Compactness feature, PLPC at 2400 BPS.



F.5.1. Scatter plot of scores, and linear regression model for the Compactness intelligibility feature, obtained with LPC-10 at 2400 BPS. Regression lines for the Voiced and Unvoiced conditions are also shown.



F.5.2. Scatter plot of scores, and linear regression model for the Compactness intelligibility feature, obtained with PLPC at 2400 BPS. Regression lines for the Voiced and Unvoiced conditions are also shown.

Intelligibility of Compactness vs. Bit Error Rate, for 2400 BPS LPC-10

Model: $S(LPC) = 95.19 - 3.432(BER\%)$ (Based on 192 points)

Bit Error Rate	Intelligibility of Compactness		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	95.2		92.38 ↔ 98.00	69.73 ↔ 120.64
1	91.8		89.58 ↔ 93.93	66.36 ↔ 117.15
2	88.3		86.48 ↔ 90.16	62.96 ↔ 113.69
3	84.9		82.93 ↔ 86.85	59.52 ↔ 110.27
4	81.5		78.99 ↔ 83.93	56.04 ↔ 106.88
5	78.0		74.84 ↔ 81.22	52.53 ↔ 103.53
6	74.6	↓	70.59 ↔ 78.60	48.98 ↔ 100.21
7	71.2	*Extrapolated*	66.29 ↔ 76.04	45.40 ↔ 96.93
8	67.7	*Values*	61.97 ↔ 73.50	41.78 ↔ 93.68
9	64.3		57.63 ↔ 70.97	38.14 ↔ 90.46
10%	60.9		53.28 ↔ 68.46	34.45 ↔ 87.28

F.6.1. Predicted intelligibility scores for Compactness, LPC-10 at 2400 BPS with bit errors (with no provisions for error protection).

Intelligibility of Compactness vs. Bit Error Rate, for 2400 BPS PLPC

Model: $S(PLPC) = 95.13 - 3.819(BER\%)$ (Based on 192 points)

Bit Error Rate	Intelligibility of Compactness		95% Confidence Limits: Expected Avg. Score	95% Confidence Limits: Individual Scores
0	95.1		92.02 ↔ 98.24	67.00 ↔ 123.26
1	91.3		88.90 ↔ 93.72	63.25 ↔ 119.37
2	87.5		85.46 ↔ 89.53	59.46 ↔ 115.52
3	83.7		81.51 ↔ 85.84	55.63 ↔ 111.71
4	79.9		77.12 ↔ 82.58	51.76 ↔ 107.94
5	76.0		72.51 ↔ 79.56	47.86 ↔ 104.21
6	72.2	↓	67.79 ↔ 76.64	43.91 ↔ 100.52
7	68.4	*Extrapolated*	63.01 ↔ 73.78	39.93 ↔ 96.86
8	64.6	*Values*	58.21 ↔ 70.95	35.90 ↔ 93.25
9	60.8		53.38 ↔ 68.13	31.85 ↔ 89.67
10%	56.9		48.55 ↔ 65.33	27.75 ↔ 86.12

F.6.2. Predicted intelligibility scores for Compactness, PLPC at 2400 BPS with bit errors (with no provisions for error protection).

LINEAR REGRESSION ESTIMATES OF INTELLIGIBILITY vs. BIT ERROR RATE

LPC-10 AT 2400 BITS PER SECOND

FORM: DRT INTELLIGIBILITY SCORE = a + bR, where R = B.E.R. in percent

INTELLIGIBILITY FEATURE	FEATURE PRESENT	FEATURE ABSENT	FEATURE AVERAGE
VOICING (Avg.)	93.7 − 5.70 R	96.2 − 4.34R	95.0 − 5.02 R
Frictional	87.3 − 3.28 R	93.8 − 5.53R	90.5 − 4.41 R
Non-Frictional	100.0 − 8.12 R	98.7 − 3.14R	99.4 − 5.63 R
NASALITY (Avg.)	99.2 − 3.78 R	98.0 − 3.69 R	98.6 − 3.73 R
Grave	97.1 − 4.48 R	97.8 − 3.54R	97.4 − 4.01 R
Acute	101.3 − 3.08 R	98.2 − 3.83R	99.8 − 3.46R
SUSTENTION (Avg.)	86.8 − 6.79 R	80.7 − 4.61R	83.8 − 5.70 R
Voiced	86.2 − 8.29 R	73.3 − 6.09R	79.7 − 7.19 R
Unvoiced	87.4 − 5.29 R	88.2 − 3.13R	87.8 − 4.21 R
SIBILATION (Avg.)	82.1 − 3.32 R	94.6 − 1.57R	88.3 − 2.45 R
Voiced	81.8 − 2.50 R	95.5 − 2.09R	88.6 − 2.30 R
Unvoiced	82.4 − 4.14 R	93.6 − 1.05R	88.0 − 2.60 R
GRAVENESS (Avg.)	82.8 − 6.05 R	83.5 − 6.74R	83.1 − 6.39R
Voiced	92.6 − 6.06 R	97.2 − 4.46R	94.9 − 5.26 R
Unvoiced	72.9 − 6.04 R	69.7 − 9.02R	71.3 − 7.53 R
COMPACTNESS (Avg.)	97.3 − 3.07 R	93.1 − 3.79R	95.2 − 3.43 R
Voiced	99.6 − 2.19 R	99.9 − 2.78R	99.8 − 2.48 R
Unvoiced	95.0 − 3.96 R	86.2 − 4.80R	90.6 − 4.38 R

TOTAL DRT INTELLIGIBILITY SCORE: 90.7 − 4.45 R

G.1. Summary of linear regression equations relating intelligibility scores and bit error rate, for individual intelligibility feature states; LPC-10 at 2400 BPS.

LINEAR REGRESSION ESTIMATES OF INTELLIGIBILITY vs. BIT ERROR RATE

10th-Order PIECEWISE-LPC (6/4) AT 2400 BITS PER SECOND

Form: DRT INTELLIGIBILITY SCORE = a + bR, where R = B.E.R. in percent

INTELLIGIBILITY FEATURE	FEATURE PRESENT	FEATURE ABSENT	FEATURE AVERAGE
VOICING (Avg.)	95.6 − 1.71 R	97.0 − 5.54R	96.3 − 3.63 R
Frictional	93.1 − 1.94 R[a]	94.3 − 5.23R	93.7 − 3.58 R
Non-Frictional	98.1 − 1.48 R	99.8 − 5.85R	98.9 − 3.67 R
NASALITY (Avg.)	98.8 − 2.58 R	97.8 − 4.73R	98.3 − 3.65 R
Grave	97.3 − 2.29 R	97.6 − 4.85R	97.4 − 3.57 R
Acute	100.3 − 2.86 R	98.1 − 4.61R	99.2 − 3.74 R
SUSTENTION (Avg.)	83.1 − 4.56 R	85.1 − 5.26R	84.1 − 4.91 R
Voiced	80.2 − 3.83R	77.2 − 5.08R	78.7 − 4.45 R
Unvoiced	85.9 − 5.30R	93.0 − 5.44R	89.5 − 5.37 R
SIBILATION (Avg.)	94.8 − 4.52 R	96.3 − 2.18 R	95.6 − 3.35 R
Voiced	95.3 − 2.91 R	93.7 − 2.31 R	94.5 − 2.61 R
Unvoiced	94.3 − 6.13 R	99.0 − 2.05R	96.6 − 4.09 R
GRAVENESS (Avg.)	84.6 − 6.73 R	86.0 − 4.76R	85.3 − 5.75 R
Voiced	97.9 − 7.38 R	96.5 − 2.45R	97.2 − 4.91 R
Unvoiced	71.4 − 6.08 R	75.5 − 7.08R	73.4 − 6.58 R
COMPACTNESS (Avg.)	98.1 − 4.85 R	92.2 − 2.79R	95.1 − 3.82R
Voiced	96.6 − 2.82R	97.6 − 1.13R	97.1 − 1.98R
Unvoiced	99.5 − 6.88 R	86.8 − 4.45R	93.1 − 5.66R

TOTAL DRT INTELLIGIBILITY SCORE: *92.5 − 4.18 R*

[a] *For this case, the value of the slope was not significant.*

G.2. Summary of linear regression equations relating intelligibility scores and bit error rate, for individual intelligibility feature states; PLPC at 2400 BPS.

EXPECTED VALUES AND 95% CONFIDENCE LIMITS
FOR BIT-ERROR REGRESSION COEFFICIENTS
LPC-10 AT 2400 BITS PER SECOND

INTELLIGIBILITY FEATURE	FEATURE PRESENT	FEATURE ABSENT	FEATURE AVERAGE
VOICING (Avg.)	-8.14≤(-5.70)≤-3.27	-5.50≤(-4.34)≤-3.17	-6.37≤(-5.02)≤-3.67
Frictional	-6.02≤(-3.28)≤- .54	-7.20≤(-5.53)≤-5.86	-5.99≤(-4.41)≤-2.82
Non-Frictional	-12.17≤(-8.12)≤-4.08	-4.31≤(-3.14)≤-1.98	-7.81≤(-5.63)≤-3.45
NASALITY (Avg.)	-5.02≤(-3.78)≤-2.54	-4.81≤(-3.69)≤-2.56	-4.56≤(-3.74)≤-2.91
Grave	-6.58≤(-4.48)≤-2.39	-5.12≤(-3.54)≤-1.97	-5.30≤(-4.01)≤-2.72
Acute	-4.24≤(-3.08)≤-1.92	-5.51≤(-3.83)≤-2.15	-4.49≤(-3.46)≤-2.43
SUSTENTION (Avg.)	-8.76≤(-6.79)≤-4.82	-6.80≤(-4.61)≤-2.42	-7.16≤(-5.70)≤-4.24
Voiced	-11.26≤(-8.30)≤-5.32	-9.25≤(-6.09)≤-2.93	-9.36≤(-7.19)≤-5.02
Unvoiced	-7.82≤(-5.29)≤-2.77	-5.17≤(-3.13)≤-1.09	-5.84≤(-4.21)≤-2.59
SIBILATION (Avg.)	-5.04≤(-3.32)≤-1.60	-2.29≤(-1.57)≤- .85	-3.56≤(-2.45)≤-1.34
Voiced	-5.16≤(-2.50)≤- .16	-3.10≤(-2.09)≤-1.08	-3.89≤(-2.30)≤- .70
Unvoiced	-6.40≤(-4.14)≤-1.89	-2.10≤(-1.05)≤-.002	-4.18≤(-2.60)≤-1.01
GRAVENESS (Avg.)	-7.71≤(-6.05)≤-4.38	-9.24≤(-6.74)≤-4.24	-7.88≤(-6.39)≤-4.91
Voiced	-7.84≤(-6.06)≤-4.29	-5.91≤(-4.46)≤-3.01	-6.47≤(-5.26)≤-4.05
Unvoiced	-8.00≤(-6.04)≤-4.07	-11.49≤(-9.02)≤-6.54	-9.18≤(-7.53)≤-5.87
COMPACTNESS (Avg.)	-4.08≤(-3.07)≤-2.07	-5.36≤(-3.79)≤-2.21	-4.38≤(-3.43)≤-2.48
Voiced	-3.03≤(-2.19)≤-1.34	-3.88≤(-2.78)≤-1.68	-3.17≤(-2.48)≤-1.80
Unvoiced	-5.55≤(-3.96)≤-2.38	-7.05≤(-4.80)≤-2.54	-5.84≤(-4.58)≤-2.92

TOTAL DRT INTELLIGIBILITY SCORE: -4.69≤(-4.45)≤-4.22

G.3. Estimated confidence limits for regression slopes:
LPC-10 at 2400 BPS.

EXPECTED VALUES AND 95% CONFIDENCE LIMITS
FOR BIT-ERROR REGRESSION COEFFICIENTS
10th ORDER PIECEWISE-LPC (6/4) AT 2400 BITS PER SECOND

INTELLIGIBILITY FEATURE	FEATURE PRESENT	FEATURE ABSENT	FEATURE AVERAGE
VOICING (Avg.)	-3.00≤(-1.71)≤- .42	-6.99≤(-5.54)≤-4.09	-4.66≤(-3.63)≤-2.59
Frictional	-4.16≤(-1.94)≤ .28[a]	-7.26≤(-5.25)≤-3.19	-5.13≤(-3.58)≤-2.04
Non-Frictional	-2.75≤(-1.48)≤- .22	-7.97≤(-5.85)≤-3.74	-5.02≤(-3.67)≤-2.31
NASALITY (Avg.)	-3.52≤(-2.58)≤-1.64	-6.01≤(-4.73)≤-3.45	-4.48≤(-3.65)≤-2.63
Grave	-5.60≤(-2.29)≤- .99	-6.74≤(-4.65)≤-2.96	-4.78≤(-3.57)≤-2.36
Acute	-4.26≤(-2.86)≤-1.47	-6.44≤(-4.61)≤-2.76	-4.92≤(-3.74)≤-2.56
SUSTENTION (Avg.)	-6.76≤(-4.56)≤-2.36	-7.09≤(-5.26)≤-3.43	-6.33≤(-4.91)≤-3.50
Voiced	-6.88≤(-5.85)≤- .76	-6.09≤(-5.08)≤-2.06	-6.57≤(-4.46)≤-2.34
Unvoiced	-6.60≤(-5.30)≤-2.00	-6.95≤(-5.44)≤-3.96	-7.17≤(-5.57)≤-3.57
SIBILATION (Avg.)	-5.66≤(-4.52)≤-3.38	-2.98≤(-2.16)≤-1.38	-4.10≤(-3.35)≤-2.60
Voiced	-4.19≤(-2.91)≤-1.63	-3.54≤(-2.51)≤-1.08	-5.48≤(-2.61)≤-1.74
Unvoiced	-7.72≤(-6.13)≤-4.55	-2.93≤(-2.05)≤-1.17	-5.32≤(-4.09)≤-2.67
GRAVENESS (Avg.)	-6.90≤(-6.73)≤-4.56	-7.06≤(-4.76)≤-2.44	-7.34≤(-5.75)≤-4.15
Voiced	-9.15≤(-7.38)≤-5.61	-3.81≤(-2.45)≤-1.08	-6.22≤(-4.91)≤-3.60
Unvoiced	-9.23≤(-6.08)≤-2.95	-9.92≤(-7.08)≤-4.24	-8.65≤(-6.56)≤-4.50
COMPACTNESS (Avg.)	-6.32≤(-4.65)≤-3.38	-4.29≤(-2.79)≤-1.26	-4.87≤(-3.82)≤-2.77
Voiced	-4.87≤(-2.82)≤- .77	-2.00≤(-1.13)≤- .26	-3.10≤(-1.98)≤- .65
Unvoiced	-6.79≤(-6.88)≤-4.97	-6.52≤(-4.45)≤-2.38	-7.11≤(-5.66)≤-4.21

TOTAL DRT INTELLIGIBILITY SCORE: -4.42≤(-4.18)≤-3.95

[a] *For this single case, the 95% confidence interval included "zero" slope; ACCEPT Hø.*

G.4. Estimated confidence limits for regression slopes:
PLPC at 2400 BPS.

INTELLIGIBILITY FEATURE SCORES: LPC-10 AT 2400 BPS

Comparing Expected Scores: Regression Model and actual data values

FEATURE	Zero B.E.R.		1%		3%		5% B.E.R.	
	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
VOICING	95.0	94.5	89.9	90.1	79.9	80.9	69.9	69.3
NASALITY	98.6	97.0	94.9	95.5	87.4	90.0	79.9	78.2
SUSTENTION	83.8	86.5	78.1	76.6	66.7	62.8	55.3	57.9
SIBILATION	88.3	88.6	85.9	85.8	81.0	79.7	76.1	76.4
GRAVENESS	83.1	83.3	76.7	76.7	63.9	63.5	51.1	51.4
COMPACTNESS	95.2	95.7	91.8	91.1	84.9	84.8	78.0	78.2

G.5.1. Comparison of actual scores for individual intelligibility features, and scores predicted by linear regression models; LPC-10 at 2400 BPS.

INTELLIGIBILITY FEATURE SCORES: PLPC AT 2400 BPS

Comparing Expected Scores: Regression Model and Actual Data

FEATURE	Zero B.E.R.		1%		3%		5% B.E.R.	
	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
Voicing	96.3	95.4	92.7	93.2	85.4	86.6	78.2	77.4
Nasality	98.3	97.2	94.7	96.1	87.3	87.2	80.0	79.8
Sustention	84.1	84.6	79.2	79.2	69.3	68.0	59.5	60.3
Sibilation	95.6	96.0	92.2	91.0	85.5	87.0	78.8	78.2
Graveness	85.3	86.8	79.6	77.7	68.1	68.2	56.6	56.9
Compactness	95.1	94.3	91.3	90.9	83.7	86.5	76.0	74.4

G.5.2. Comparison of actual scores for individual intelligibility features, and scores predicted by linear regression models; PLPC at 2400 BPS.

INTELLIGIBILITY FEATURE SCORES: LPC-10 AT 2400 BPS

Comparing Predictions from Regression Model, and actual data:

Intelligibility Scores exceeded by 97-1/2% of the data population

FEATURE	Zero B.E.R.		1%		3%		5% B.E.R.	
	Predicted	*Actual*	*Predicted*	*Actual*	*Predicted*	*Actual*	*Predicted*	*Actual*
Voicing	58.7	62.5	53.8	53.1	43.8	34.4	33.6	-21.9
Nasality	76.4	81.3	72.7	78.1	65.3	62.5	57.7	40.6
Sustention	44.6	59.4	39.0	34.4	27.6	18.8	16.0	12.5
Sibilation	58.6	46.9	56.2	46.9	51.3	56.3	46.3	21.9
Graveness	43.4	46.9	37.1	40.6	24.3	15.6	11.4	3.1
Compactness	69.7	81.3	66.4	59.4	59.5	53.1	52.5	46.9

G.5.3. Comparison of intelligibility feature scores predicted by confidence limits, with actual data distributions; LPC-10 at 2400 BPS.

INTELLIGIBILITY FEATURE SCORES: PLPC AT 2400 BPS

Comparing Predictions from Regression Model, and actual data:

Intelligibility Scores exceeded by 97-1/2% of the data population

FEATURE	Zero B.E.R.		1%		3%		5% B.E.R.	
	Predicted	*Actual*	*Predicted*	*Actual*	*Predicted*	*Actual*	*Predicted*	*Actual*
Voicing	68.7	78.1	65.1	68.8	57.9	56.3	50.5	28.1
Nasality	76.1	78.1	72.5	81.3	65.2	53.1	57.8	46.9
Sustention	46.2	34.4	41.4	40.6	31.6	15.6	21.6	12.5
Sibilation	75.5	78.1	72.2	75.0	65.5	68.8	58.7	34.4
Graveness	42.7	53.1	37.0	37.5	25.6	9.4	13.9	- 6.3
Compactness	67.0	68.8	63.3	71.9	55.6	62.5	47.9	28.1

G.5.4. Comparison of intelligibility feature scores predicted by confidence limits, with actual data distributions; PLPC at 2400 BPS.

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

Reference: EFFECTS OF BIT ERRORS ON TOTAL DRT INTELLIGIBILITY SCORES FOR LPC AND PLPC AT 2400 BPS.

Nr. of rows ("A" 's): [Processor Configurations: LPC and PLPC, at 2400 BPS] 2= I

Nr. of columns ("B" 's): [Speakers] 6= J

Nr. of levels ("C" 's) : [Bit Error Rates] 4= K

Nr. of replications ("M"): [Total DRT Scores from 8 listeners x 2 presentations] 16= M

Values by rows:

LPC at 2400 BPS.

Zero bit error rate. Test #2050.

Spkr LL	83.33	93.75	89.58	88.54	89.58	89.58	92.71	87.50
	89.58	86.46	92.71	88.54	92.71	92.71	91.67	89.58
Spkr RH	86.46	87.50	90.62	88.54	93.75	86.46	89.58	89.58
	92.71	86.46	88.54	86.46	87.50	90.62	90.62	90.62
Spkr CH	92.71	94.79	94.79	94.79	93.76	90.62	93.75	92.71
	89.58	94.79	93.75	92.71	92.71	94.79	91.67	93.75
Spkr PK	87.50	92.71	92.71	88.54	86.46	94.79	90.62	91.67
	95.83	90.62	92.71	91.67	90.62	94.79	88.54	92.71
Spkr JE	88.54	89.58	91.67	90.62	90.62	85.42	88.54	87.50
	90.62	90.62	92.71	93.75	88.54	88.54	91.67	88.54
Spkr BV	91.67	95.83	92.71	90.62	92.71	90.62	88.54	92.71
	90.62	94.79	95.83	93.75	91.67	91.67	88.54	89.58

1% bit error rate. Test #2051.

Spkr LL	83.33	89.58	84.37	86.46	83.33	85.42	82.29	86.46
	82.29	88.54	83.33	83.33	88.54	79.17	90.62	80.21
Spkr RH	83.33	88.54	88.54	86.46	85.42	90.62	90.62	86.46
	87.50	90.62	87.50	90.62	87.50	89.58	85.42	83.33
Spkr CH	91.67	83.33	88.54	92.71	86.46	92.71	89.58	91.67
	94.79	89.58	91.67	88.54	92.71	90.62	91.67	91.67
Spkr PK	76.04	79.17	80.21	85.42	79.17	76.04	79.17	75.00
	83.33	81.25	80.21	85.42	90.62	83.33	83.33	83.33
Spkr JE	82.29	84.37	81.25	81.25	81.25	87.50	84.37	83.33
	82.29	85.42	81.25	86.46	91.67	85.42	86.46	83.33
Spkr BV	87.50	89.58	88.54	89.58	86.46	81.25	87.50	86.46
	87.50	88.54	87.50	89.58	89.58	87.50	84.37	87.50

H.I. Data Table: Total DRT Intelligibility Scores for LPC and PLPC at 2400 BPS with bit errors.

TOTAL DRT INTELLIGIBILITY SCORES FOR LPC AND PLPC AT 2400 BPS - continued.

(LPC at 2400 BPS-continued)
3% bit error rate. Test #2052.

Spkr LL	79.17	80.21	77.08	71.87	70.83	68.75	80.21	76.04
	75.00	78.12	79.17	80.21	71.87	72.92	73.96	75.00
Spkr RH	79.17	82.29	80.21	79.17	78.12	81.25	82.29	79.17
	78.12	83.33	76.04	78.12	66.75	80.21	77.08	82.29
Spkr CH	85.42	84.37	86.46	84.37	85.42	85.42	77.08	73.96
	86.46	81.25	79.17	83.33	84.37	90.62	80.21	80.21
Spkr PK	68.75	73.96	70.83	75.00	72.92	72.92	70.83	69.79
	76.04	72.92	79.17	82.29	73.96	75.00	73.96	65.62
Spkr JE	70.83	70.83	68.75	75.00	66.67	75.00	76.04	71.87
	75.00	68.75	77.08	69.79	78.12	73.96	75.00	70.83
Spkr BV	71.87	71.87	81.25	82.29	78.12	75.00	79.17	81.25
	82.29	77.08	73.96	81.25	86.46	81.25	78.12	77.08

5% bit error rate. Test #2053.

Spkr LL	62.50	69.79	69.79	66.67	63.54	69.79	70.83	76.04
	65.62	69.79	68.75	72.92	71.87	67.71	70.83	69.79
Spkr RH	72.92	71.87	65.62	70.83	66.67	70.83	61.46	69.79
	66.67	56.25	66.67	68.75	72.92	58.33	65.62	70.83
Spkr CH	70.83	78.12	76.04	73.96	76.04	71.87	73.96	80.21
	70.83	76.04	81.25	75.00	72.92	73.96	71.87	76.04
Spkr PK	70.83	60.42	61.46	64.58	69.79	69.79	72.92	55.21
	62.50	64.58	63.54	67.71	62.50	71.87	66.67	59.37
Spkr JE	55.21	71.87	65.62	64.58	62.50	65.62	61.46	58.33
	66.67	59.37	66.67	62.50	63.54	63.54	63.54	61.46
Spkr BV	73.96	72.92	72.92	60.42	79.17	66.67	72.92	72.92
	80.21	75.00	63.54	73.96	67.71	67.71	67.71	76.04

PLPC at 2400 BPS.

Zero bit error rate. Test #2043.

Spkr LL	93.75	92.71	90.62	88.54	90.62	91.67	92.71	86.46
	89.58	95.83	88.54	91.67	89.58	88.54	92.71	92.71
Spkr RH	91.67	93.75	93.75	85.42	96.87	92.71	94.79	92.71
	89.58	96.87	94.79	94.79	94.79	92.71	93.75	92.71
Spkr CH	98.96	97.92	96.87	96.87	95.83	93.75	94.79	92.71
	95.83	97.92	94.79	94.79	94.79	94.79	94.79	95.83
Spkr PK	90.62	94.79	92.71	90.62	91.67	89.58	92.71	92.71
	91.67	98.96	90.62	92.71	90.62	89.58	90.62	90.62
Spkr JE	86.46	88.54	87.50	85.42	92.71	91.67	91.67	82.29
	87.50	88.54	88.54	91.67	90.62	89.58	89.58	87.50
Spkr BV	91.67	94.79	91.67	94.79	94.79	91.67	93.75	92.71
	94.79	93.75	95.83	94.79	93.75	92.71	96.87	91.67

H.I. =continued (part 2).

TOTAL DRT INTELLIGIBILITY SCORES FOR LPC AND PLPC AT 2400 BPS - continued.

(PLPC at 2400 BPS - continued)

1% bit error rate. Test #2047.

Spkr LL	90.62	91.67	85.42	93.75	86.46	85.42	78.12	91.67
	86.46	85.42	90.62	91.67	90.62	91.67	92.71	89.58
Spkr RH	92.71	91.67	87.50	92.71	93.75	91.67	87.50	90.62
	90.62	88.54	94.79	91.67	92.71	88.54	89.58	86.46
Spkr CH	91.67	89.58	92.71	93.75	90.62	85.42	91.67	85.42
	92.71	90.62	96.87	91.67	90.62	90.62	68.54	95.83
Spkr PK	89.58	80.21	75.00	84.37	88.54	86.46	86.46	80.21
	85.42	86.46	86.46	84.37	91.67	83.33	83.33	85.42
Spkr JE	88.54	82.29	80.21	90.62	84.37	84.37	89.58	81.25
	86.46	82.29	91.67	81.25	90.62	81.25	65.42	80.21
Spkr BV	89.58	85.42	85.42	89.58	87.50	90.62	89.58	85.42
	87.50	83.33	94.79	90.62	85.42	83.33	86.46	85.42

3% bit error rate. Test #2048.

Spkr LL	80.21	79.17	84.37	80.21	81.25	82.29	82.29	72.92
	88.54	86.46	77.08	87.50	84.37	80.21	83.33	80.21
Spkr RH	82.29	82.29	82.29	77.08	85.42	80.21	75.00	87.50
	82.29	78.12	80.21	86.46	73.96	86.46	83.33	82.29
Spkr CH	85.42	79.17	82.29	82.29	87.50	82.29	84.37	82.29
	81.25	81.25	78.12	81.25	87.50	83.33	78.12	80.21
Spkr PK	79.17	75.00	67.71	75.00	77.08	79.17	73.96	78.12
	80.21	78.12	73.96	83.33	78.12	77.08	72.92	71.87
Spkr JE	83.33	78.12	79.17	82.29	75.00	78.12	82.29	76.04
	80.21	84.37	85.42	85.42	81.25	85.42	79.17	83.33
Spkr BV	82.29	81.25	72.92	77.08	84.37	82.29	77.08	72.92
	83.33	78.12	82.29	87.50	81.25	79.17	82.29	79.17

5% bit error rate. Test #2049.

Spkr LL	77.08	68.75	70.83	72.92	66.67	77.08	77.08	80.21
	76.04	82.29	79.17	77.08	77.08	71.87	72.92	80.21
Spkr RH	72.92	80.21	66.67	76.04	79.17	75.00	67.71	77.08
	71.87	81.25	77.08	79.17	70.83	79.17	75.00	72.92
Spkr CH	77.08	76.04	76.04	72.92	79.17	73.96	77.08	70.83
	73.96	75.00	75.00	75.00	70.83	75.00	73.96	75.00
Spkr PK	64.58	66.67	61.46	56.25	65.62	61.46	66.67	61.46
	61.46	61.46	57.29	62.50	59.37	64.58	64.58	62.50
Spkr JE	68.75	67.71	63.54	75.00	68.75	69.79	58.33	59.37
	68.75	77.08	69.70	69.79	68.75	65.62	68.75	67.71
Spkr BV	60.42	71.87	66.67	69.79	78.12	69.79	73.96	67.71
	71.87	71.87	75.00	76.04	68.75	67.71	78.12	73.96

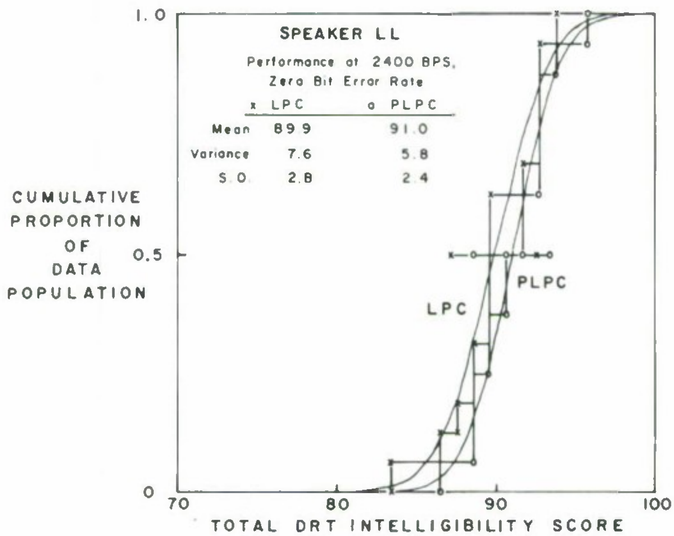
H.I.-continued (part 3).

THREE-WAY ANALYSIS OF VARIANCE (m OBS. PER CELL)

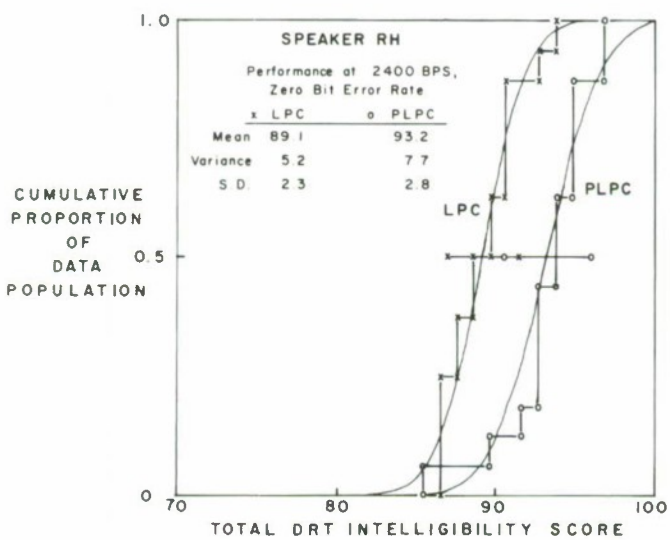
Reference: EFFECTS OF BIT ERRORS ON TOTAL DRT INTELLIGIBILITY SCORES FOR LPC AND PLPC AT 2400 BPS.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F ratio
Replications	15	422.10998	28.14066	
"A" 's (processors)	1	1108.97008	1108.97008	96.31848 *** (p=.9999)
"B" 's (speakers)	5	4703.95355	940.79071	81.71143 *** (p=.9999)
"C" 's (BER's)	3	52874.81167	17624.93722	1530.79623 *** (p=.9999)
AB Interactions	5	525.97760	105.19552	9.13665 *** (p=.9999)
AC Interactions	3	107.84994	35.94998	3.12239 * (p=.9741)
BC Interactions	15	1175.58178	78.37211	6.80693 *** (p=.9999)
ABC Interactions	15	883.72137	58.91475	5.11698 *** (p=.9999)
Error	705	8117.07036	11.51357	
Total	767	69920.04633		

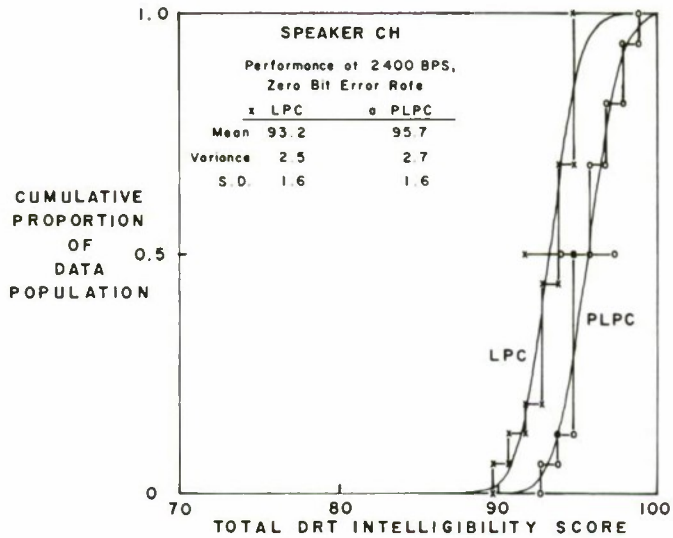
H.2. Analysis of Variance Summary: Total DRT Intelligibility Scores.



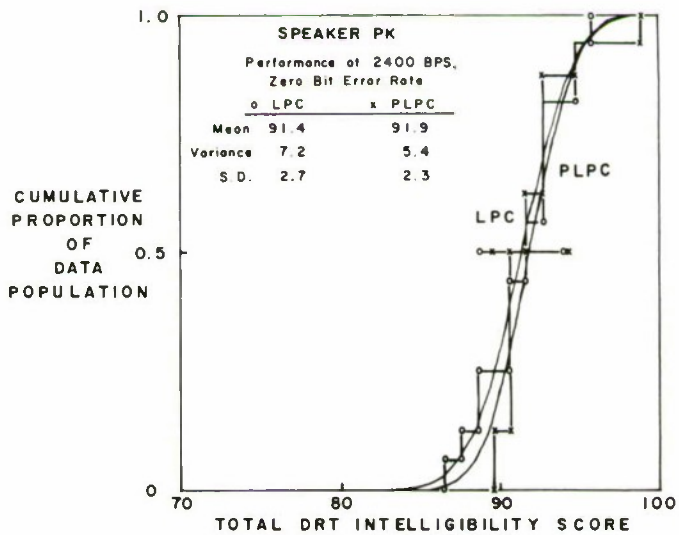
H.3.1. Comparison of distributions of total DRT intelligibility scores of Speaker LL: LPC-10 and PLPC at 2400 BPS.



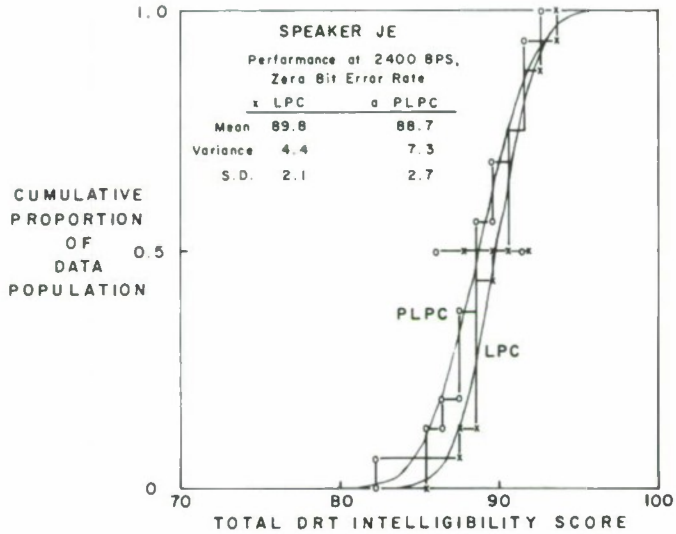
H.3.2. Comparison of distributions of total DRT intelligibility scores of Speaker RH: LPC-10 and PLPC, at 2400 BPS.



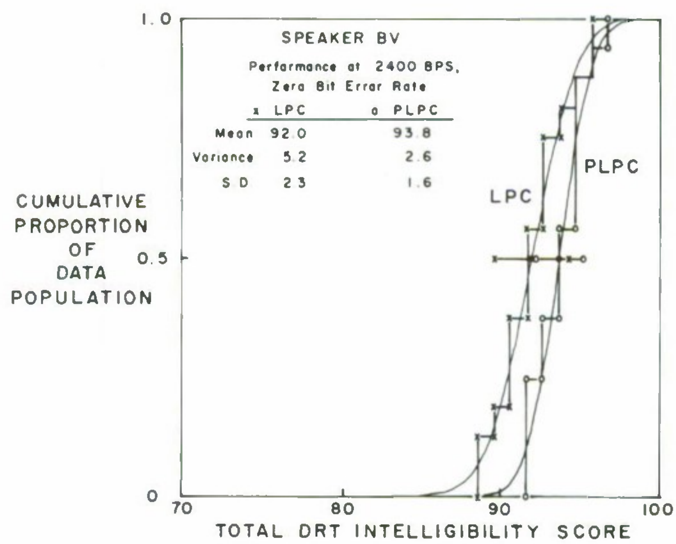
H.3.3. Comparison of distributions of total DRT intelligibility scores of Speaker CH: LPC-10 and PLPC, at 2400 BPS.



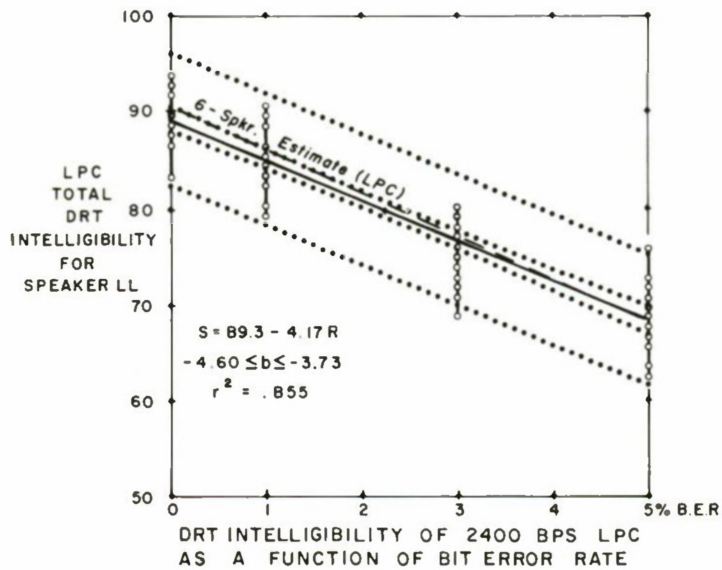
H.3.4. Comparison of distributions of total DRT intelligibility scores of Speaker PK: LPC-10 and PLPC, at 2400 BPS.



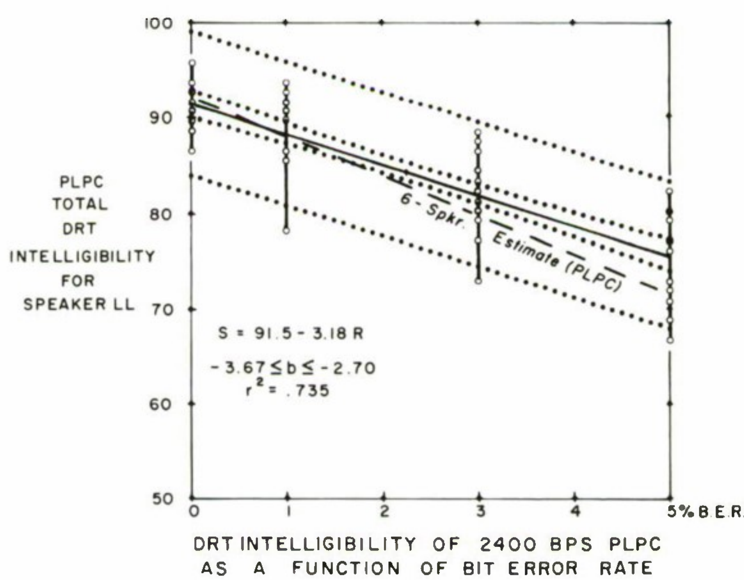
H.3.5. Comparison of distributions of total DRT intelligibility scores of Speaker JE: LPC-10 and PLPC, at 2400 BPS.



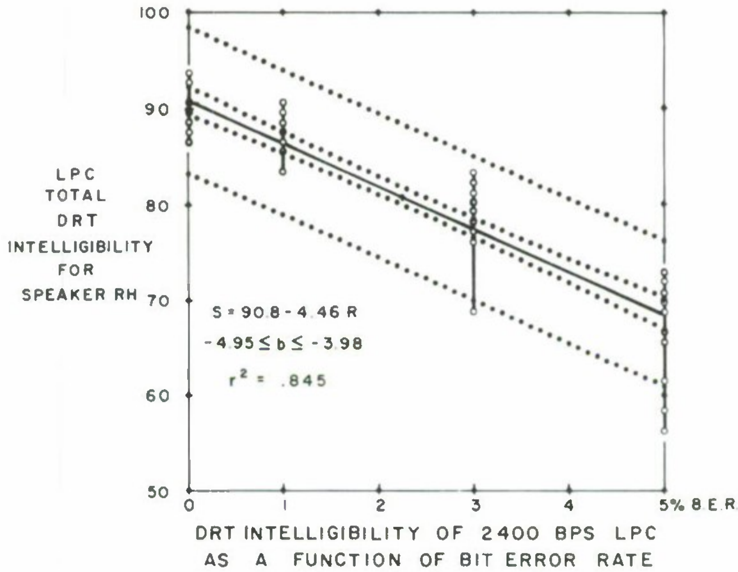
H.3.6. Comparison of distributions of total DRT intelligibility scores of Speaker BV: LPC-10 and PLPC, at 2400 BPS.



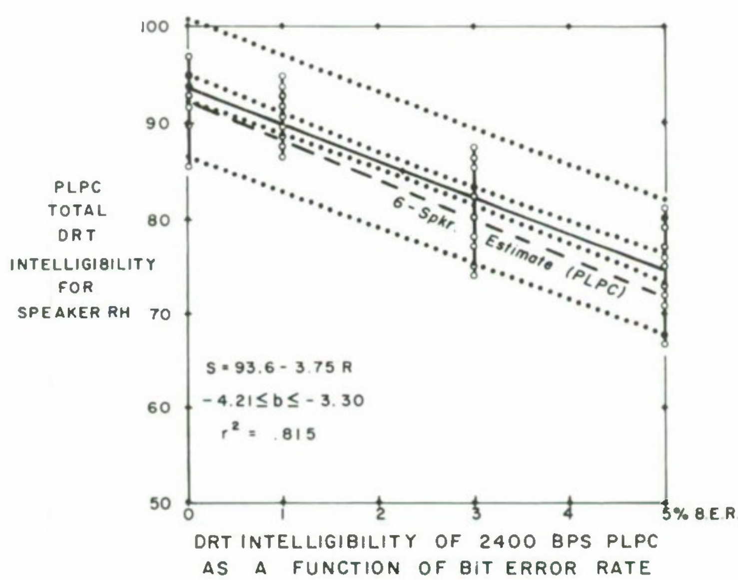
H.4.1.A. Scatter plot of scores, and linear regression model for the total DRT Intelligibility scores of Speaker LL, with LPC-10 at 2400 BPS. The 6-speaker regression line is also shown.



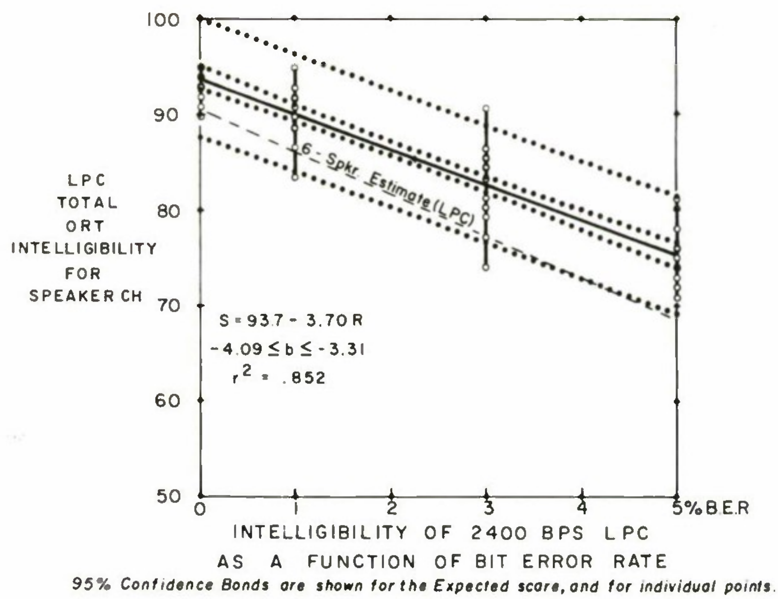
H.4.1.B. Scatter plot of scores, and linear regression model for the total DRT Intelligibility scores of Speaker LL, with PLPC at 2400 BPS. The 6-speaker regression line is also shown.



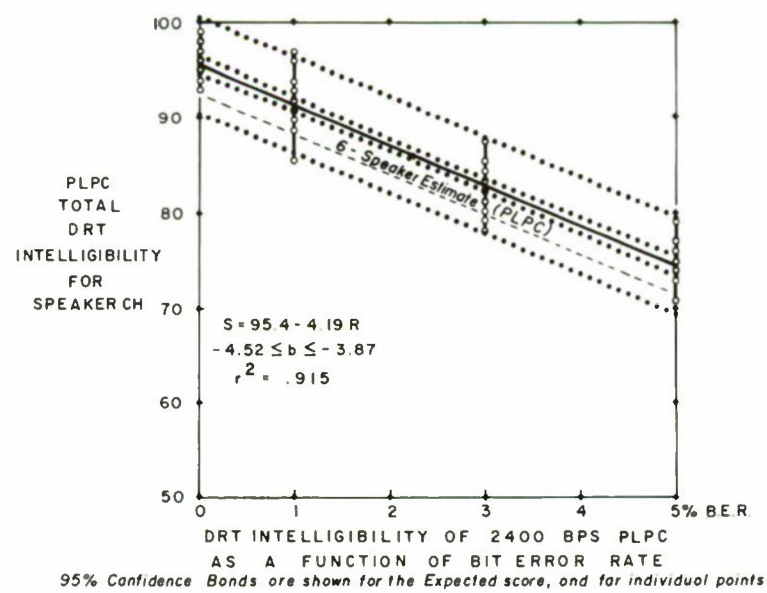
H.4.2.A. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker RH, with LPC-10 at 2400 BPS.



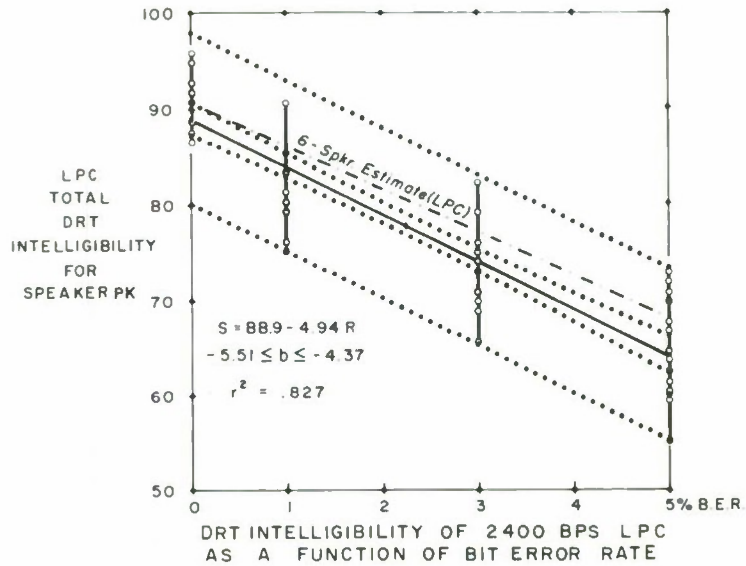
H.4.2.B. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker RH, with PLPC at 2400 BPS.



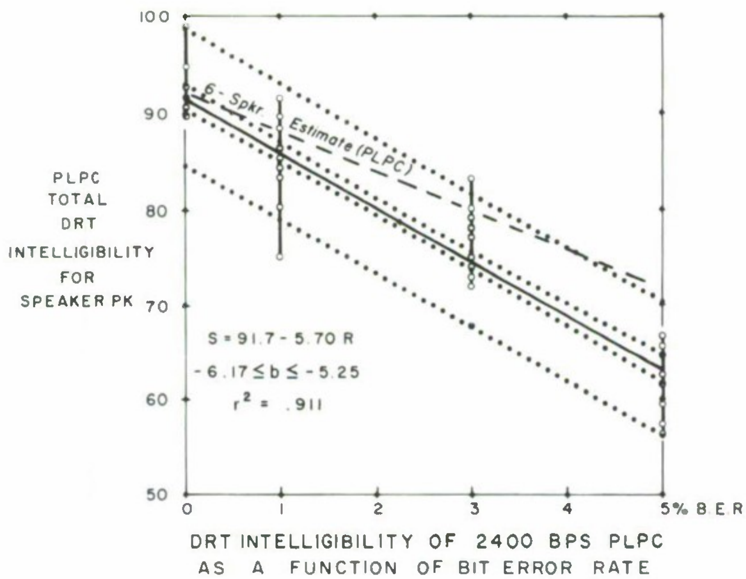
H. 4. 3. A. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker CH, obtained with LPC-10 at 2400 BPS.



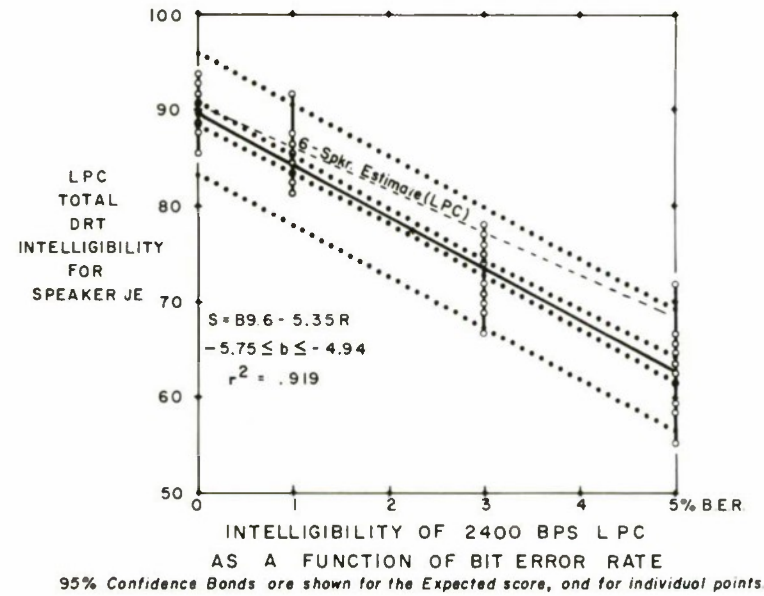
H. 4. 3. B. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker CH, obtained with PLPC at 2400 BPS.



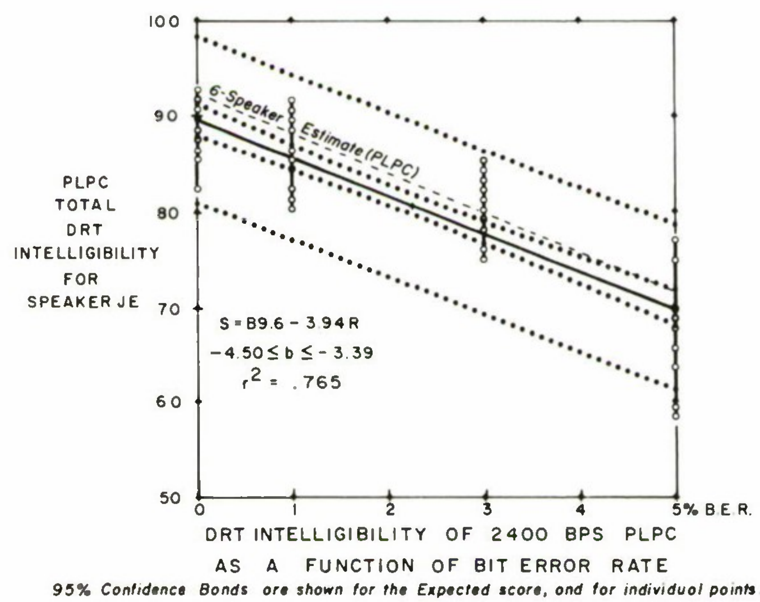
H. 4. 4. A. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker PK, obtained with LPC-10 at 2400 BPS.



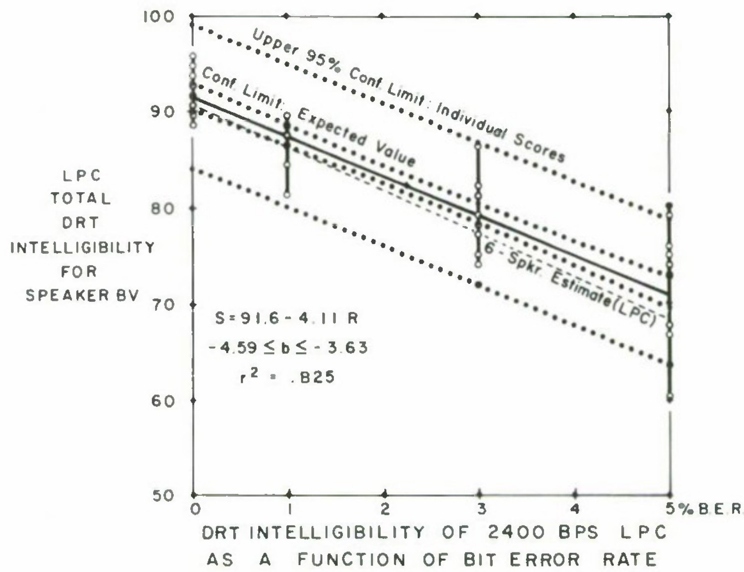
H. 4. 4. B. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker PK, obtained with PLPC at 2400 BPS.



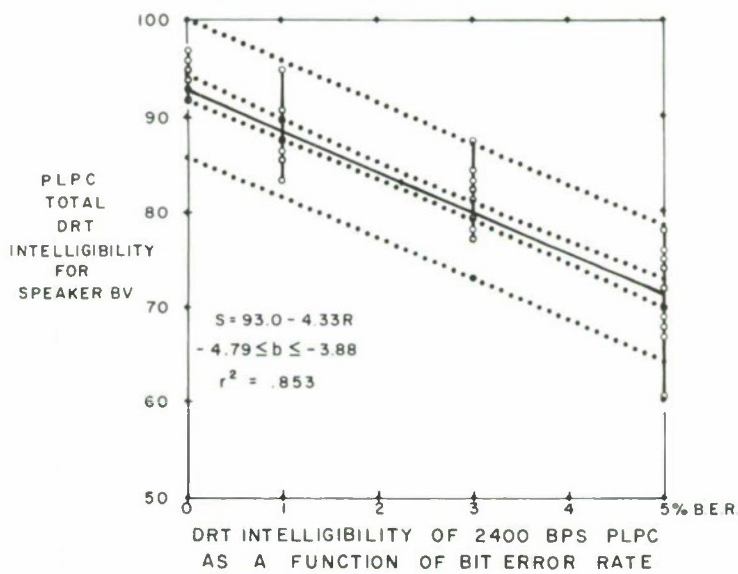
H.4.5.A. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker JE, obtained with LPC-10 at 2400 BPS.



H.4.5.B. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker JE, obtained with PLPC at 2400 BPS.



H. 4. 6. A. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker BV, obtained with LPC-10 at 2400 BPS.



H. 4. 6. B. Scatter plot of scores, and linear regression model for the total DRT intelligibility scores of Speaker BV, obtained with PLPC at 2400 BPS.

APPENDIX I. STATISTICAL FORMULATIONS.

1.1. Linear regression.

Given an esnemble of paired measurement data Xi, Yi $(i = 1,2,\dots n)$ where the Xi are values of an independent variable (in this report, bit error rates expressed in percentage points) and the Yi are associated values of a dependent variable (here, intelligibility scores obtained at the specified bit error rates), the n values of X and Y can be characterized by sample means

$$\bar{X} = \frac{1}{n} \sum_{1}^{n} Xi \quad , \quad \bar{Y} = \frac{1}{n} \sum_{1}^{n} Yi$$

estimating the "true" mean values μ_x , μ_y of the sampled populations. Given the mean values, the datum points can be expressed in terms of deviations from the mean values:

$$x_i = (Xi - \bar{X}) \quad , \quad y_i = (Yi - \bar{Y})$$

and sums of squared deviations from the means can be calculated:

$$\Sigma x^2 = \Sigma (X - \bar{X})^2 \quad , \quad \Sigma y^2 = \Sigma (Y - \bar{Y})^2$$

$$= \Sigma X^2 - (\Sigma X)^2/n \qquad = \Sigma Y^2 - (\Sigma Y)^2/n$$

Sums of products of deviations can also be calculated

$$\Sigma xy = \Sigma (X - \bar{X})(Y - \bar{Y}) = \Sigma XY - (\Sigma X)(\Sigma Y)/n$$

leading to a determination of a sample regression coefficient expressing values of Y expected per unit of X:

$$b = \Sigma xy / \Sigma x^2$$

The sample regression equation estimating values of Y in terms of X is expressed

$$\hat{Y} = \bar{Y} + bx$$

or, in terms of deviations from the mean,

$$\hat{y} = bx$$

In terms of the original units,

$$\hat{Y} - \bar{Y} = b(X - \bar{X})$$

The sum of squared deviations of values of the dependent variable Y from the regression line can be expressed

$$\Sigma dy.x^2 = \Sigma y^2 - \left[(\Sigma xy)^2 / \Sigma x^2\right]$$

leading to an expression for the mean square deviation

$$sy.x^2 = \Sigma dy.x^2 / (n-2)$$

and an estimate of the standard deviation of the regression coefficient

$$s_b = sy.x / \sqrt{\Sigma x^2} \qquad \text{with (n-2) degrees of freedom.}$$

A test of significance of the slope b is given by

$$t = b / s_b \qquad \text{with (n-2) degrees of freedom.}$$

The sample regression coefficient b, an estimate of the "true" population regression slope β can be used in estimating a confidence interval for the "true" regression slope, based on the fact that

$$(b - \beta) / s_b$$

follows Student's t-distribution with (n-2) degrees of freedom. Consequently a 95% confidence interval for the "true" regression slope can be expressed

$$b - t_{.05} s_b \leq \beta \leq b + t_{.05} s_b$$

Based on an assumption that errors in estimating the elevation and the slope of the regression line are independent, their errors are uncorrelated, and the variance of the sum of the two errors is the sum of the two error variances. Consequently

$$\sigma_{\hat{y}}^2 = \sigma_{y.x}^2 (1/n + x^2/\Sigma x^2)$$

and the standard error in estimating the expected value $\hat{Y}$ is

$$s_{\hat{y}} = s_{y.x} \sqrt{1/n + (x^2 / \Sigma x^2)}$$

with (n-2) degrees of freedom.

As a consequence, a confidence interval can be estimated for any $\hat{Y}$ estimating the "true" expectation μ :

$$\hat{Y} - t_{\alpha;n-2}\, s_{\hat{y}} \leq \mu \leq \hat{Y} + t_{\alpha;n-2}\, s_{\hat{y}}$$

A confidence interval for estimating individual values of Y', given values of X, can also be established, based on an assumption that the mean square error in predicting individual Y' can be expressed

$$s'^2_{\hat{y}} = \frac{s_{y.x}^2}{n} + \frac{x^2 s_{y.x}^2}{\Sigma x^2} + s_{y.x}^2$$

leading to a standard error for this prediction:

$$s'_{\hat{y}} = s_{y.x} \sqrt{1 + 1/n + \frac{x^2}{\Sigma x^2}}$$

The corresponding 95% confidence interval for predicting individual datum points is

$$Y - t_{.05}\, s'_{\hat{y}} \leq Y' \leq Y + t_{.05}\, s'_{\hat{y}}$$

In comparing regression lines obtained from different sample populations, the question arises whether the regression lines can be considered to be equivalent, in terms of their slopes, elevations, and/or residual variances (mean square deviations from their regression lines).

The residual variances of two regression lines can be compared with the two-tailed F-test, or for more than two regression lines, can be compared with Bartlett's test.

Assuming homogeneity of residuals, the slopes can be compared by means of the variance ratio of the mean squares: (Diff. between slopes)/("within" slopes), in conjunction with the F-test with 1 and k degrees of freedom, where k is the sum of the d.f. for deviations from regression, for the individual regression lines.

The meansquare for "difference between slopes" is expressed

$$MS(\text{"diff"}) = \Sigma_1 \Sigma_2 (b_1 - b_2)^2 / (\Sigma_1 + \Sigma_2)$$

where Σ_1, Σ_2 are the values of Σx^2 for two regression lines.

With more than two regression lines,

$$\text{MS(diff.between slopes)} = \Sigma w_i (b_i - \bar{b})^2$$

where $w_i = 1/\Sigma_i$, $\bar{b} = \Sigma w_i b_i / \Sigma w_i$

(The sum of squares of deviations of the b's is a weighted sum, because the variances of the b_i, namely $\sigma_{y.x}^2/\Sigma_i$ depend on the values of Σx^2).

The linear regression model assumes the existence of populations of intelligibility scores related to specified bit error conditions, the relationship being such that average scores at each bit error rate condition lie on a straight line, the population regression line, defined

$$\mu = a + \beta(X - X) = a + \beta x$$

where a and β are parameters.

The parameter a is the mean score at x = 0, specifying the elevation of the regression line when $X = \bar{X}$.

The value of β ,the slope of the regression line, is negative for

these data, since an increase in bit error rate caused a decrease in intelligibility scores. In this context, the slope parameter b has the nature of a figure of merit that estimates susceptibility of a processor/speaker/intelligibility feature combination to the effects of bit errors.

The linear regression equations for total intelligibility scores as a function of bit error rate represented the composite average relationship based on intelligibility scores of all of the speakers, and all of the intelligibility features. The data for individual speakers involved identical numbers of sample points at each bit error rate, for each speaker. Consequently the value of Σx^2 was identical in the normal regression equations for each speaker's scores. The result of this identity was that the values of slope and elevation in the regression equation for the average performance of all speakers were the average values of the slopes and elevations respectively of the individual speakers.

A similar effect occurred in regard to scores for individual intelligibility features (averaged across all speakers). Here also there were identical values of Σx^2 in the equations for each intelligibility feature; this identity resulted in the values of slope and elevation in the regression equation for total intelligibility being the averages of the slopes and elevations respectively of regression equations for the individual feature scores.

The linear regression formulation is based on

$$Y = \alpha + \beta x + \epsilon$$

with values of the dependent variable expressed as a linear sum of three terms, the error term ϵ representing a normally distributed random variable, independent of x, with zero mean and standard deviation $\sigma_{y.x}$.

For any x, $\hat{Y}$ provides an estimate of the "true" expectation corresponding to the given x value. Since

$$\hat{Y} - \mu = (\bar{Y} - \alpha) + (b - \beta) x$$

it is seen that difference between the estimate and the "true" expectation μ has two sources, both due to the random term ϵ : a difference of elevations, and a difference of slopes.

Thus the model is based on assumptions that the variance or spread of the distribution of values of the dependent variable (here, the intelligibility scores) is the same at every value of the independent variable (here, the bit error rate), and that the distribution of values of Y at each value of x is normal. These assumptions can be

tested with tests for homogeneity of variance, and tests for conformity with a normal curve. Where the data distributions fail to conform with these assumptions, results of significance tests are in question. However, such results, taken in combination with an examination of the actual data distributions that occurred, may provide insights as to the nature and degree of relationship between the variables under examination.

I.2. Lilliefor's Test for conformity with normal distribution.

The Lilliefor's test for goodness of fit is a statistic of the Kolmogorov-Smirnov type, in which a random sample from some unknown distribution is tested in order to test the null hypothesis that the unknown distribution is in fact a known, specified function, in this case, normally distributed.

The data population consisting of a random sample $x_1\ x_2 \dots x_n$ of size n is used to compute the sample mean:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

for use as an estimate of the "true" mean μ, and the standard deviation:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

as an estimate of the "true" value of σ.

Sample points are converted to "normalized" sample values defined by

$$z_i = \left(\frac{x_i - \bar{x}}{s}\right) \qquad i = 1, 2, \dots n$$

The test is computed from the z_i's rather than the original datum points. The normalized data, the z_i's defined above, are used in constructing a cumulative distribution function. The normal cumulative distribution is also constructed, based on the values of μ and σ. The magnitude of the difference between the (normalized) data distribution and the normal ogive is calculated for each datum, to determine the maximum difference. This difference is the Lilliefor's test statistic, defined by

$$T_2 = \sup_x | F^*(x) - S(x) |$$

The decision rule in Lilliefor's test is to reject Ho at the approximate level of significance a if T_2 exceeds a critical value set forth in Lilliefor's tables, which are published in Conover (1971) (see Bibliography).

For $n > 30$, the critical value for p = .95 is $.886/\sqrt{n}$. and for p= .99 is $1.031/\sqrt{n}$.

I.3. Bartlett's Test for homogeneity of variance.

Where more than two independent estimates of variance are to be tested to determine whether there are significant differences, a test has been provided by Bartlett, as follows.

If there are g estimates s_i^2, each with the same number of degrees of freedom f, the test criterion is

$$M = L\,f\,(g \operatorname{Log} \bar{s}^2 - \sum \operatorname{Log} s_i^2)$$

where L is a constant 2.3026 = Ln(10).

On the null hypothesis that each s_i^2 is an estimate of the same σ^2 , the quantity M/C is distributed approximately as χ^2 with (g-1) degrees of freedom, where

$$C = 1 + \frac{g+1}{3\,g\,f}$$

It has been observed that this test is sensitive to non-normality in the data, particularly to kurtosis. Data populations with a long "tail" to the distribution, i.e. with positive kurtosis, tend to result in biased results towards decisions of heterogeneity.

I.4. Comparison of two data populations by paired samples.

In a pairwise analysis, the data to be analyzed is converted to a sample of n <u>differences</u> in measurement (in this case, differences between intelligibility scores taken pairwise). The members of each pair have one or more factors in common (in this analysis each pair were intelligibility scores from the same speaker, and at the identical bit error rate). Pairing has the effect of normalizing for average differences (such as the average differences between speaker means, and between mean scores at the various bit error rates) that might otherwise tend to obscure differences between the two entities under comparison (here, the LPC and PLPC voice processors).

The analysis of paired data involves assumptions that differences D_i between individual pairs are distributed about a mean μ_D which represents the "true" average difference between the entities being compared.

The deviations $D_i - \mu_D$ are assumed to be normally and independently distributed with population mean zero.

When these assumptions hold, the sample mean difference $\bar{D}$ is normally distributed about μ_D with standard error $\sigma_D \sqrt{n}$ where σ_D is the standard deviation of the population of differences.

The value of σ_D is estimated from $S_D = \sqrt{\dfrac{\Sigma(D_i - \bar{D})^2}{n-1}} = \sqrt{\dfrac{\Sigma D_i^2 - (\Sigma D_i)^2/n}{n-1}}$

and $\quad S_{\bar{D}} = S_D / \sqrt{n}$

provides an estimate of $\sigma_{\bar{D}}$ based on n-1 degrees of freedom.

As a result, the quantity

$$t = (\bar{D} - \mu_D) / S_{\bar{D}}$$

follows Student's t-distribution with n-1 degrees of freedom, where n is the number of pairs, thus permitting confidence limits to be constructed for the mean difference, and tests of the null hypothesis (that the mean difference is zero).

$$\bar{D} - t_{\alpha;\nu}\, S_{\bar{D}} \leq \mu_D \leq \bar{D} + t_{\alpha;\nu}\, S_{\bar{D}}$$

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